Pre-cooling of ton-scale particle detectors in low radioactivity environments

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Abstract. Low radioactivity sites are mandatory to perform searches for rare processes that cannot be studied with particle accelerators and requires low environmental backgrounds. Neutrino-less double $\beta$ decay or Dark Matter searches must be performed in underground low radioactivity observatories. Large detectors are needed to increase the acceptances and proper cryogenic systems to run dedicated detectors. To reach the working temperatures, refrigerators as Pulse Tubes, Dilution Units are used inside complex cryostats. CUORE, Cryogenic Underground Observatory for Rare Events, is an experiment located at LNGS under the Gran Sasso mountain. So far, it’s the coldest cubic meter and the largest cold mass ever realized. Its 998 TeO$_2$ bolometers need to be kept at temperatures $T< 10$ mK. Using only Pulse Tubes, CUORE needs several weeks to reach the baseline $T$. Then a Fast Cooling System has been designed and constructed for a faster precooling of the whole CUORE cold volume. The Fast Cooling System (FCS) consists of a cryostat with heat exchangers that use 3 Gifford-McMahon refrigerators, a $^4$He compressor, a filtering module and several sensors that allow to monitor and control the system during CUORE cooldown. The present work describes the FCS and summarizes its performances during the first full CUORE cooldown.

1. Introduction

The search for neutrino-less double beta decay ($0\nu2\beta$) and Dark Matter (DM) requires the use of very sensitive low rate detectors. Currently crystal bolometers are the best detector candidates thanks to their high sensitivity and low background. A bolometer is a device for measuring the energy of incident radiation with a very low energy threshold. It consists of an absorptive element (absorber) connected to a heat sink (a body of constant temperature) through a thermal coupling, as shown Fig.1. Several dielectric and diamagnetic materials can act as a low energy particle absorber, and a wide range of such
Materials are available as double beta decay emitters ($^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{130}$Te). Most of the bolometric detectors need to be operated at very low temperatures ($\sim$10 mK) while situated in a low radioactivity site. The acceptance for both 0ν2β and DM events strongly depends on the detector mass (counts/keV·kg·yr). Increasing the detector mass also means a longer and more challenging cool down process to obtain a very low operating temperature. Thus, the cooling systems have a crucial role for this kind of research.

CUORE [1] is an experiment, currently taking data, at Laboratori Nazionali del Gran Sasso (LNGS) of Istituto Nazionale di Fisica Nucleare (INFN) in Italy. It is based on low temperature calorimeter technology, called bolometers [2]. At this time, it is the coldest cubic meter and the largest cold mass ever realized experimentally. Its purpose is to search for rare events such as 0ν2β in $^{130}$Te. The CUORE detector consists of an array of 988 TeO$_2$ crystals arranged in a structure of 19 towers as shown in Fig. 1 (left). The CUORE cryostat, see Fig.1 (right), is a custom apparatus consisting of six nested copper shields, related plates, a cryogen free cooling system with five Pulse Tubes (Cryomech PT415) and a very powerful Dilution Refrigerator (DR). The six shields are for the different temperature stages of the system: 300 K, 40 K, 4 K, 600 mK, 50 mK, and 10 mK. The PTs are thermally linked to 40 K and 4 K stages. The DR can operate once the temperature is below 4K. At base temperature, only four PTs are kept on; so one spare PT can be used in case of problems. The entire cryostat is suspended from a Main Support Plate (MSP), which bears the load of the system totaling close to 20 tons.

2. The Fast Cooling System
The Fast Cooling System (FCS) has been designed for a quicker pre-cooling of CUORE detector, from room temperature down to 40-50 K in about two weeks [3]. It consists of cryogen free coolers (the five PTs) and an external system that flows cold He inside the CUORE Inner Vacuum Chamber (IVC). This external system involves a Fast Cooling Unit (FCU), containing a primary and secondary heat exchanger, a gas compressor, double-walled flexible pipes, a filtering system and several other components and sensors. The FCU is cooled down by three Cryomech AL600 Gifford-McMahon
cryocoolers (GM), each with a cooling power of about 600 W at 77 K. To avoid damages to the TeO$_2$ crystals, the temperature gradient ($T_{\text{from cryostat}} - T_{\text{to cryostat}}$) is kept below 40K, the pressure inside the entire system has to be $950 \text{ mbar} < P < 1360 \text{ mbar}$ and finally the He flux cannot exceed 5 g/s. The general schematic of the FCS is presented in Fig.2.

2.1. Fast Cooling Unit
The FCU mainly consists of two nested vessels containing two internal heat exchangers, cooled by the three GM heads. It has been constructed in The Netherlands by Leiden Cryogenics™ [4]. One internal heat exchanger (HEX) is made of copper and it is the coldest part of the FCU; the other is a counter-flow HEX; they correspond to HEX2 and HEX1 respectively as seen in Fig.2. The HEX1 is an 8 m long, counter-flow heat exchanger and has a spiral shape as shown in Fig.2 (right). It is made of metal double pipe bellows with an external diameter of 62 mm. The HEX2 is made of Oxygen-Free High thermal Conductivity (OFHC) copper and it consists of a stack of sixty-five disks, separated by 3 mm spacers, suspended by three copper rods; its total weight is about 300 kg. As shown in Fig.2, the HEX2 is connected to a steel flange that is thermally linked and mechanically supported by the three GM cryocoolers. To keep the inner part as cold as possible, HEX2 is then surrounded by an internal shield, called the Inner Fast Cooling Chamber (IFC) shown in Fig.2. In turn, the IFC is surrounded by the Outer Fast Cooling Chamber (OFC), which is kept under vacuum in order to prevent heat transfer by convection from room temperature to the IFC. Moreover, cryogenic multi-layer insulation is added over the entire internal surface to avoid heat transfer by radiation. The gas inlet and outlet valves, as well as all the sensor plugs, are located on the top flange of FCU.

2.2. FCS Helium Circuit
The Helium gas in the FCS is drawn from a dewar located at the ground floor of CUORE’s hut (a 3 floor building). As shown in Fig.2 (left), the source of $^4$He is connected to the FCS circuit by means of a Mass Flow Controller (MFC). This is used as a valve to inject He in the circuit both manually and automatically during the cool down phase. The He gas enters the compressor flowing through the compressor pre-filter at pressure $P_1$ and exits the compressor at pressure $P_2$. After the compressor, the gas flows through a Flow Meter (FM), which measure the g/s of He circulating in the FCS. It then enters the FC Filtering Module (FCFM) which consist of three different filters: Fine, Superfine and High-Efficiency Particulate Air (HEPA) filters. The MFC, the compressor, the FM, and the FCFM are located at the ground floor of the CUORE hut. The gas leaves the ground floor and reaches the second floor.

Figure 2. Schematic Overview of the Fast Cooling System (left); the Fast Cooling Unit (right).
passing through a 12 m long bellows flex line. Then it enters a 4 m long counter-flow heat exchanger, HEX0, and finally reaches the FCU. The gas enters the FCU through a valve and reaches the second heat exchanger, HEX1, which is located in the bottom part of the FCU. The ⁴He leaves HEX1 at a reduced temperature and enters the IFC where the coldest heat exchanger (HEX2) is located. After being cooled by HEX2, the gas leaves the IFC going to the CUORE cryostat. Since this is the coldest part of the circuit, a double-walled bellows flex line is used. After cooling the CUORE IVC, the gas goes back to the FCU where, passing through HEX1 and HEX0, it goes back to the compressor to start again the circulation. The gas is now at room temperature due to the heat exchanging with the inflowing gas on the way back.

2.3. FCS Data Acquisition System
Temperature and pressure are the critical variables to be kept under control. The temperature of both the FCS and the CUORE cryostat is acquired via numerous thermometers all over the system. Three different types of thermometers are used: two Platinum (PT100, PT1000) and one Silicon Diode (DT470). In the most critical parts redundant thermometers are present for monitoring so that no excessive thermal stress is applied to the delicate crystal detector. The pressure of CUORE IVC during the cool down is strictly dependent on the frequency of the compressor and the pressure of the FCS. The lowest value of pressure needs to be always higher than atmospheric pressure in order to prevent air from entering the FCS and consequently the CUORE cryostat (contamination problems); however, the pressure in the FCS circuit cannot exceed a threshold set by the IVC o-ring seal to avoid damage. This threshold has been evaluated as 1.36 bar. Thus, the FCS is equipped with several pressure gauges in order to monitor the system behaviour and to have a feedback signal for self-regulation. Apart from the thermometry, which has a dedicated electronics setup, the remaining devices are monitored and controlled by means of three DAQ boards. All the instruments are then connected to a dedicated PC.

3. Fast Cooling Monitor and Control System
The whole FCS is monitored and controlled by a dedicated slow control system. The Fast Cooling Monitor and Control System (FCMCS) consists of several LabView based Virtual Instruments (VIs) organized in a more general slow control architecture. It not only acquires all the needed information from different instrumentation, with different protocols, but then supervises by using developed

![Figure 3. CUORE Fast Cooling Unit Monitor Panel, all critical parameters are redundantly monitored.](image-url)
strategies and logics the FCS activities during the entire cool down process that is very critical and risky in several aspects. The temperature of the FCU, as well as the He entering the CUORE IVC, need to be continuously monitored and kept in a specific range. A CUORE Fast Cooling Unit Monitor Panel has been developed, as shown in Fig.3. The temperature values of all the thermometers related to the FCU, the high side and low side pressure in the He circuit, and their time evolution plots are displayed along with a map showing the position of each thermometer to help the operator be aware of the FCS status. The main control interface, called the Fast Cooling System Control Panel, is depicted in Fig.4. It contains all the crucial information to make the FCS work properly (i.e. compressor frequency, pressures, alarm thresholds, cryocoolers control). The operator can directly act on the system as well as activate the Automatic Control Algorithm (ACA). The ACA allows setting the min and max limits for the pressure resulting in an automatic refill of the He circuit by means of a Mass Flow Controller (i.e. the lower the temperature, the lower the pressure) and opens a safety valve in case of overpressure. Numerous safety alarms and actions have been developed which give the operator the ability to automatically adjust the compressor frequency in order to keep cooling the cryostat in the most efficient fashion. Several other interfaces allow extra features such monitoring the cryostat temperature, plotting the cooling speed for each single thermometer and a global temperature monitor with comparison plots.

4. CUORE Pre-cooling Performances
Several months of preparation and test runs have been performed between 2014 and 2015 in order to characterize the system. The final CUORE cryogenic cool down (without the ~1 ton crystal detector installed into it), took place in November 2015 and is referred to as Run 4 [5]. The cooldown started by means of the FCS alone (no PTs). After three days, the five PTs had been switched on. The FCS was then turned off at a temperature of approximately 60 K. The FCS brought the CUORE cryostat from 300 K to 60 K in about 10 days. A summary of the cooldown can be found in Fig.5 (top). During the summer of 2016 the complete detector was installed adding a mass of about 809 kg (742 kg of TeO₂ plus copper). In this configuration, the cooldown of the complete CUORE (Run I) started by means of the Fast Cooling System [6]. It was operated for 10 days, cooling the cryostat down to around 100 K as shown in Fig.5 (bottom). Three PTs, out of five, have been switched on along the cool down process. At the beginning of Run I, the compressor frequency was progressively increased up to 18 Hz (corresponding to a He flow of about 2.8 g/s); it was kept around that frequency for several days. The cooling speed, where the bolometers are located, reached a peak value of (1.09±0.02) K/h, stabilizing.
around (0.90±0.02) K/h for a majority of the time, and decreasing to (0.49±0.02) K/h in the last twelve hours of the pre-cooling. Taking into account the tremendous thermal inertia (~20 tons) of CUORE, the described performance can be considered good. In the last hours, the compressor frequency was progressively lowered to 13 Hz and then to 10 Hz before the final decision to switch off the system, at higher temperature than expected for testing of other apparatus. It has been proved that the design specifications have been matched [7].

5. Conclusions
A Fast Cooling System has been designed, constructed, tested and finally used for a faster pre-cooling of ton-scale bolometric experiments searching for Neutrino-less Double Beta Decay and Dark Matter. It has been operated on the CUORE cryostat (around 20 tons mass) at Laboratori Nazionali del Gran Sasso, Italy. The FCS brought the significantly large mass of CUORE’s cryostat and crystal detectors below 100 K in 10 days successfully, with a mean cooling speed of approximately 0.71 K/h, proving the good performance of the system. The whole system has been equipped with numerous sensors in order to have precise control of the cool down process via the Fast Cooling Monitor and Control System software. It allows automatic and manual control of the entire FCS together with alarms and safety actions in case of dangerous anomalies. In future cooldowns, the possibility to simultaneously turn on FCU + 5 PTs at the beginning of the pre-cooling will guarantee better performance. Finally, this system is suitable for every experiment that needs a large cryostat (big mass) in a low radioactivity environment with the need to speed up the pre-cooling phase.

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