ABSTRACT: This paper reports the detailed noise characterization, investigation of various noise sources and its mitigation to improve the performance of a cryogenic bolometer detector. A sapphire bolometer test setup with indigenously developed NTD Ge sensor is mounted in the CFDR system at TIFR and the noise spectrum in the frequency range of DC–25 kHz has been measured using a NI based data acquisition (DAQ) system. The noise and its influence have been studied for the complete setup including the system related diagnostics as well as control electronics, and the readout electronics together with the DAQ. The DAQ and readout electronics consist of multiple channels of high precision DAC and ADC, distribution boards, high input impedance - high gain preamplifiers, multi-core twisted pair cables as well as the multi-channel twisted pair wiring internal to the cryostat. The effect of external noise, arising either from ground loops in the system or from the diagnostic and control electronics of the cryostat, on the performance of a cryogenic bolometer is assessed. A systematic comparison of the influence of different noise pickups on the bolometer resolution is also presented. The best achieved resolution ($\sigma_E$) at 15 mK is $\sim$ 15 keV for heater pulses and is mainly limited by the pulse tube cryocooler.

KEYWORDS: Cryogenic detectors, instrumental noise, double beta decay detectors

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1. Introduction

Over the last few decades, the interest in cryogenic bolometer detectors has increased significantly, with applications in various fields of physics ranging from spectroscopy to rare event studies like dark matter search [1–3]. One of the attractive aspects of cryogenic bolometer detectors is the good energy resolution. Recently, there is tremendous growth in diverse experiments related to neutrino physics [4]. Study of the mass and nature of neutrino plays a pivotal role in understanding the new physics beyond the standard model of particle physics. At present, neutrinoless double beta decay (NDBD) is the most sought after experiment to study the mass and nature of the neutrino [5–7]. The excellent energy resolution, sensitivity and a possibility to upscale the size, makes the cryogenic bolometer detector an ideal choice for rare decay experiments like NDBD. An experiment to study NDBD in $^{124}$Sn, TIN.TIN (The INdia based TIN detector), has been initiated in India [8].

The resolution achieved with cryogenic bolometers is often not limited by the intrinsic resolution of the bolometer, but by the external noise sources in the system. The intrinsic resolution of the bolometer depends only on the bolometer temperature and the heat capacity, and is extremely small as compared to the contribution due to external factors [1]. For example, the intrinsic resolution ($\sigma_E$) of a TeO$_2$ bolometer ($5 \times 5 \times 5$ cm$^3$) is expected to be $\sim$ 10 eV at 10 mK, while experimentally the best resolution achieved is $\sim$ 2.13 keV (FWHM $\sim$ 5 keV) [9]. In the case of microbolometer ($< 10$ µg), resolution $\sim$ few eV has been reported [10]. Therefore, a major challenge for these experiments is to minimize the contribution of external noise originating from the cryogenic system and the associated electronics. Noise induced due to the mechanical vibrations is one of the major drawbacks in a pulse tube based cryogenic system. The effect of mechanical vibrations can propagate to the lowest temperature stage and result in heating of the sensor, thereby affecting the performance of the bolometer. In addition to acting as an additional thermal load, these vibrations can also couple to the signal lines causing microphonic noise pickup in the readout signal. Hence, some attempts to reduce the contribution of pulse tube induced vibrational noise by implementing special vibrational damping measures during the design of the cryostat have been reported [11–13]. Other major contribution in the external noise sources involves the intrinsic noise of the mK thermometer and that induced by
the front-end electronics. Apart from these widely known external factors, there can be system specific noise sources like vacuum pumps and measurement units. An efficient and proper ground connection of the system is necessary in order to minimize the ground loops, which otherwise can result in noise pickups in the operating frequency range. These various sources of pickups can have a detrimental effect on the overall performance of the bolometer and therefore, it is essential to investigate and eliminate the same.

With this motivation, we have studied the noise and its influence on a test bolometer in the cryogen free dilution refrigerator (CFDR-1200) system at TIFR [14]. The cryogenic bolometer consists of a sapphire absorber and employs an indigenously developed neutron transmutation doped (NTD) Ge sensor for mK thermometry. The detailed noise measurements in the frequency span of DC – 25 kHz have been carried out for the entire setup including the system related diagnostics, control systems, NI-based data acquisition (DAQ) system and the readout electronics. The DAQ and readout electronics consist of multiple channels of high precision DAC and ADC, distribution boards, high input impedance-high gain preamplifiers, multi-core twisted pair cables as well as the multi-channel twisted pair wiring internal to the cryostat. An efficient grounding configuration is implemented to minimize the ground loops in the system. Several measures are taken to minimize or eliminate unwanted pickups originating from various control and diagnostic modules of the cryogenic system, mainly the vacuum pumps and vacuum gauges. Consequently, an improvement in the minimum achievable base temperature and in the temperature of NTD sensor has been observed. The resolution of the bolometer is also evaluated at 15 mK by applying external heater pulses. Significant improvement has been observed in the resolution of the bolometer. This paper presents the details of noise sources, measured noise levels over a wide frequency range and corrective measures implemented to improve the performance of a cryogenic bolometer.

2. Bolometer test setup

A custom built CFDR-1200 system has been set up for the prototype development of a Sn cryogenic bolometer (See Figure 1) and to study the various thermometry aspects of a cryogenic bolometer. The CFDR-1200 is equipped with a two stage pulse tube cryocooler (Cryomech-PT415). To minimize the mechanical vibrations produced by the pulse tube, a linear drive unit is used to smoothen the motion of the rotary valve. A carbon Speer sensor, calibrated against a Cerium Magnesium Nitrate (CMN) thermometer, is mounted on the mixing chamber (MC) plate and is used to monitor the MC temperature. The more detailed description of the CFDR-1200 is available in Ref. [14]. For thermal load minimization, the readout wires from the MC stage (mK) to the top of the cryostat (~300 K) are designed to be very long and consequently are prone to external electromagnetic interference (EMI) pickup. Hence, the complete CFDR setup is enclosed within a Faraday cage to reduce the effect of EMI on the measurement. A special arrangement has also been made to detach the motor control unit of the pulse tube cooler from the cryostat body to minimize the effect of pulse tube vibration.

Presently, a sapphire bolometer test setup is developed and mounted at the MC stage to study the various thermometry features of a cryogenic bolometer as shown in Figure 2. It consists of a 0.4 mm thick sapphire absorber plate of dimension 20 mm × 20 mm. Two NTD Ge sensors and a heater element are strongly coupled to the sapphire bolometer with the help of a thin layer of low temperature araldite.
The sapphire plate is connected to the gold plated Cu block using tiny dots of araldite (Dia. ~ 1 mm, Thickness ~ 0.1mm), which provide a weak thermal link and also minimize the heat capacity of the addendum. The heater element is developed by evaporating a 200 nm thick Au meander on a Si substrate. In the present measurements, the heater is used as a source of external phonon signal. The resistance of the heater element, as measured using an AC resistance bridge AVS-47B, is found to be ~ 0.6 kΩ at 1 K and remains constant over the temperature range of 1 K down to 10 mK. The NTD Ge sensors of dimension 6 mm × 3 mm × 1 mm are developed in-house by irradiating a Ge crystal with thermal neutrons in Dhruva reactor at BARC [15]. The required electrical connections for the NTD Ge sensor and the heater are made via a wedge bonded Al wire (~ 25 µm) connected with the Cu pads on a printed circuit board (PCB) [16]. The connections from the Cu pad are finally routed to the 300K stage of the

Figure 1. The CFDR-1200 dilution refrigerator setup at TIFR
cryostat using twisted pair shielded cables. All the readout cables are fitted with clip-on EMI ferrite core filter at either end of the cable. The electrical circuit schematic to test the performance of sapphire bolometer is shown in Figure 3. The resistance of NTD Ge is measured by applying a pseudo-constant current square pulse and measuring the voltage pulse across the sensor. The current is generated by applying a voltage square pulse, connected in series with a very high value bias resistor $R_L$ \( R_L/2 = 10 \, G\Omega \). In the present case, since the typical value of the sensor resistor $R_S$, ~ few hundreds of M\(\Omega\), is much less as compared to $R_L$, the current through the sensor is given by $I_B \approx V_B/R_L$ and is approximately constant. The voltage pulse across the sensor is then amplified using a low noise, high gain differential amplifier (Femto DLPVA-100-F) and the output of the amplifier is acquired using a PXI card from National

![Figure 2. A Schematic view of the sapphire bolometer setup](image)

![Figure 3. A schematic circuit for the sapphire bolometer readout](image)
Instruments (NI PXI-6281). The applied voltage ($V_B$) is generated from the analog output channel of the PXI card. At higher temperatures (>100 mK), the NTD Ge resistance is measured with AVS-47B as the value of the resistance is below 2 MΩ.

To measure the resolution of the sapphire bolometer, an external phonon signal is generated by applying a current pulse to the heater element and measuring the voltage across the NTD sensor. The resistance of the heater element ($R_H \approx 0.6$ kΩ) is substantially smaller as compared to the series resistor $R_L$ ($R_L \approx 2$ MΩ), thus making a constant current pulse of magnitude $I_H \approx V_B / R_L$. The heater pulse, a 200 µs square wave with a repetition rate of 2 Hz, is generated from the analog output channel of the PXI card. The voltage across the NTD sensor is recorded after amplification and analysed off-line [17].

3. Measurement and results

The resistance of NTD Ge with temperature can be expressed using Mott-Anderson law [18] as given by Eq. (1).

$$R(T) = R_0 \exp \left( \frac{T_0}{T} \right)^{1/2}$$

Here, $R_0$ and $T_0$ are constant which depends on the geometrical factors and the doping level of the Ge. In the present experiment, only Sensor-1 (DB27) is used for assessing the performance of bolometer. The resistance ($R_S$) for the DB27 has been measured as a function of mixing chamber temperature ($T_{MC}$) in the range of 10 – 400 mK. The resistance data in the temperature range of 100 – 400 mK is fitted with Eq. (1) and $R_0$ and $T_0$ are found to be 10.2 (0.5) Ω and 12.2 (0.2) K, respectively.

It was observed that the measured resistance of DB27 showed deviation from the Mott behaviour below 50 mK and saturated at ~ 250 MΩ, even though the mixing chamber cools down to 10 mK. This can happen due to the heat load from the external factors such as various noise pickups and the pulse tube induced mechanical vibrations, which can be the limiting factors for the sensor cool down. Therefore, noise spectra have been recorded using NI based DAQ system and FFT analysis was done to understand different noise sources. All noise measurements are done at the MC temperature ($T_{MC}$) of 10 mK and the voltage gain of the amplifier is fixed at 80 dB. As mentioned earlier, one of the major factors limiting the bolometer performance can be inefficient ground connections involving several ground loops. A schematic block diagram showing the optimized grounding scheme of different modules of the setup is shown in Figure 4. Along with the CFDR cryostat, the NTD sensor readout system consisting of differential amplifier and DAQ signal box, the AVS preamplifier for diagnostic thermometry of different stages of the cryostat and the AVS preamplifier for the NTD sensor readout at 300K are enclosed within a Faraday Cage. The CFDR controls for $^3$He-$^4$He gas handling system (GHS) and accessories are routed through an optically isolated USB – RS232 interface. The other modules such as PXI chassis, AVS resistance bridges and PCs for acquisition and control are fitted in an anodized metallic rack (outside the Faraday cage). The PXI is connected to the PC with an optical link to reduce external EMI pickups. For minimizing the ground loops, a specially designated clean earth pit is set up in the laboratory and ground connections are fanned out from this hub to various units as shown in Figure 4. The power line ground for different PCs for control and acquisition, PXI chassis and AVS resistance bridge is also derived from the clean earth pit.
The PXI chassis acts as a master ground for the DAQ signal box, the differential amplifier, the AVS preamplifier box as well as the cryostat. The instrument rack, which is directly grounded, is also kept isolated from the body of the different extension boards used for power connections to various instruments.

Figure 5 shows the noise spectra in the frequency range of 0 to 500 Hz for an optimal and a sub-optimal ground configuration. As an example of a ground loop in the sub-optimal grounding, the master ground is assigned to the cryostat body, which results in multiple ground connections for DAQ – through the cryostat body as well as through the power connection. In
this configuration, the peak at 50 Hz with a magnitude of -50 dB is clearly visible. Higher order harmonics of 50 Hz are also visible in the sub-optimal ground configuration. In the optimized configuration, the 50 Hz noise component is below the sensitivity of the measurement, namely, -76 dB. It is observed that $T_{MC}$ could not be stabilized at 10 mK in the sub-optimal ground configuration. Therefore, $T_{MC}$ is stabilized at a higher temperature of 15 mK with still current ($I_{\text{Still}}$) of 20 mA. It should be pointed out that both the sensor resistance and the resolution of the bolometer are very sensitive to the ground configuration.

Further noise measurements have been carried out with optimal grounding at $T_{MC} = 10$ mK for four configurations:
Case-I: pulse tube operating with a normal drive, motor head mounted on the cryostat
Case-II: pulse tube operating with a linear drive, motor head detached from the cryostat
Case-III: pulse tube operating with the linear drive, motor head detached from the cryostat, electronics of IVC (Inner Vacuum Chamber) vacuum gauge disconnected
Case-IV: pulse tube operating with the linear drive, motor head detached from the cryostat, electronics of all vacuum gauges disconnected

Noise spectra for the above four configurations are measured with a fixed voltage gain of 80 dB and are shown in Figures 6 to 9. The FFT spectra are taken over a wide frequency range of 0 – 25 kHz and are divided into four blocks with the frequency range of 20 Hz, 500 Hz, 2 kHz and 25 kHz. Initially, the noise spectra for DB27 are recorded with the pulse tube in normal drive mode to assess the impact of the pulse tube motor vibration. In Figure 6, noise peaks at 9.75 Hz, 11.25 Hz and a broad peak at 140 Hz are mainly contributed by the harmonics of 1.4 Hz, pulse tube induced noise. Pickups at frequency 827 Hz and 985.5 Hz are contributed by

![Figure 6. FFT spectra of the amplifier output for DB27 sensor for Case I (See text for details)](image-url)
vacuum pumps of the CFDR. There are several peaks in the 25 kHz window, with a dominant pair of peaks around 16 kHz with an output voltage of -55 dB. This pickup around 16 kHz is found to originate from the vacuum gauges in the CFDR system. It was noticed that this noise at 16 kHz is also sensitive to the ground loop and found to increase to -32 dB in the sub-optimal ground configuration compared to -55 dB in the optimal grounding. As mentioned earlier, the linear drive mode for the pulse tube operation is preferable at low temperature for reducing the

Figure 7. FFT spectra of the amplifier output for DB27 sensor for Case II (See text for details)

Figure 8. FFT spectra of the amplifier output for DB27 sensor for Case III (See text for details)
vibrational noise. Additionally, the pulse tube motor head is isolated from the cryostat for further reduction in vibration. In the noise spectra for Case II (Figure 7) reduction in noise peaks at 9.75 Hz, 11.25 Hz and 140 Hz is evident. Thus operating the pulse tube in linear drive helps in cooling the DB27 sensor, which is also reflected in the higher saturation value of the resistance of 370 MΩ as compared to 250 MΩ for Case I.

Figure 8, corresponding to the Case III, shows that the noise peak at 16 kHz almost vanishes after disconnecting the IVC gauge electronics and the measured resistance of the sensor was 440 MΩ. The heat load in the system is further reduced after disconnecting all other vacuum gauge electronics (Outer Vacuum Chamber, Probe and Still) of the CFDR system. The FFT spectra of the amplifier output corresponding to Case IV is shown in Figure 9. No significant changes are observed in the FFT spectra of Case III and Case IV, but its effect is seen on the cooling of the sensor. The resistance of the sensor now saturates at 594 MΩ as compared to 440 MΩ in Case III. Details of the various frequency components of the noise pickups at different stages of system improvements (Cases I to IV) are summarised in Table I.

Except for the Case I, where the pulse tube is operating in normal drive mode, the pulse tube noise is not visible in the FFT spectra. The noise spectrum continues to show several frequency peaks, albeit small. The residual noise is seen to be generated by the pulse tube system, which is verified by momentarily shutting off the pulse tube cryocooler.

The measured resistances in the temperature range of 10 – 400 mK for the above mentioned cases are shown in Figure 10, where the effect of eliminating different noise sources is evident. It can be seen from the figure that the DB27 sensor resistance has increased substantially in case IV as compared to that obtained in Case I. However, it still shows a deviation from the standard Mott curve, but the temperature at which deviation occurs is lower indicating a net improvement in the cooling of sensor.
Table 1. Amplitudes for different frequencies as measured from the noise spectra shown in Figures 6 to 9. (NV: Not Visible)

| Frequency   | Output noise voltage (dB) |
|-------------|---------------------------|
|             | Case-I | Case-II | Case-III | Case-IV |
| 9.75 Hz     | -64    | NV      | NV       | NV      |
| 11.25 Hz    | -62    | NV      | NV       | NV      |
| 140 Hz      | -70    | NV      | NV       | NV      |
| 543.5 Hz    | -63    | -62.5   | -62      | -63     |
| 827.5 Hz    | -64    | -65.7   | -70.4    | -71.6   |
| 985.5 Hz    | -62    | -58.3   | -60.4    | -60.2   |
| 15.73 kHz   | -55    | -59     | NV       | NV      |
| 16.27 kHz   | -55    | -59     | NV       | NV      |

Figure 10. Measured resistance of the NTD Ge sensor DB27 for Case-I to Case-IV in the temperature range of 10 – 400 mK. The fit to data in 100 – 400 mK range with the standard Mott curve ($R_0 = 10.2 (0.5)$ Ω and $T_0 = 12.2 (0.2)$ K) is also shown for comparison.

The effect of ground loops was also reflected in the minimum temperature achieved at MC and in the measured resolution of the bolometer. In the best configuration (Case-IV), the lowest temperature of ~ 5 mK (as measured with CMN) could be achieved as compared to 6.7 mK in
the sub-optimal ground configuration. A comparison of bolometer resolution for the case-IV configuration with sub-optimal and optimal grounding is shown in Figure 11. It is observed that resolution of the bolometer worsens by ~ 80% (from 15 keV to 27 keV) in case of a sub-optimal ground configuration. The resolution of the bolometer is found to improve by ~ 30% when the pulse tube is switched from the normal drive (Case-I) to the linear drive (Case-II). However, different configurations with the pulse tube in linear drive mode (i.e. Case-II to Case-IV) yield similar results within measurement errors (~ 15 keV) for the bolometer resolution.

4. Conclusion

In this paper, we have presented the influence of various noise sources on the performance of a sapphire test bolometer in the CFDR system inclusive of control, diagnostic thermometry and NI PXI DAQ. It is shown that the presence of ground loops can worsen the performance of bolometer by ~ 80%. Further, the noise pickup from vacuum pumps and vacuum gauge readout units also introduces thermal load on the NTD Ge sensor. In the best configuration, $\sigma_E \sim 15$ keV is obtained for the sapphire bolometer at 15 mK with the heater pulses.

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