Implementation of a Cryogenic Amplifier Into a Cryostat Chamber

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Abstract

There are many different methods of studying quantum computing. Electron Spin Resonance is the method we use, which requires the amplification of the response signal. The current amplifier works at room temperature and produces results with similar response level and noise level, making signal processing more difficult. To improve the signal-to-noise ratio of the system, the implementation of a cryogenic low noise amplifier into the cryostat will be beneficial for Electron Spin Resonance, replacing the room temperature amplifier. In order to implement this device, protection of the amplifier from a high power input signal is necessary, and can be accomplished through the use of a Single Pole Double Throw switch, given that the timing of the switch triggering is well researched. Design of a holder for the amplifier in the cryostat, with considerations of the necessity of a heat load, are also necessary. We have successfully designed a holder and determined that a heat load is not necessary for our apparatus through low Kelvin temperature testing of the amplifier. It is also evident that the cryogenic amplifier designed for low Kelvin temperatures is effective at amplifying, with a higher signal-to-noise ratio and a lower noise figure than the previous room temperature low noise amplifier. Some foundational testing on the switch has been done to lay the groundwork for its use with the amplifier, and more will be needed to fine tune the system to ensure protection of the amplifier.

Contents

1 Introduction

Electron Spin Resonance (ESR), is a method used to analyze quantum samples with different spin systems. ESR can be used to study Molecular Nanomagnets (MNM's), which are spin systems that can be designed to have specific quantum properties. For Professor Collett's lab, we are studying these MNM's as quantum bits (qubits) in order to further our understanding of the quantum computing field. Qubits are spin systems that can be in a superposition of states, allowing for more possibilities and computing power than a traditional computer binary bit [1].

Signal processing in ESR can be difficult because it involves cooling down a sample to low Kelvin temperatures, sending in pulses to that sample which elicits a response with a very low power level. That response can be amplified in order to get a signal, but in doing so, pre-existing background noise also gets amplified and can blur the signal. Our current apparatus uses a room temperature low noise amplifier, which amplifies anything that it receives. Since the amplifier is at room temperature, it has a higher noise level than a component at lower temperatures [2].

The goal of this Thesis is to improve the signal processing by implementing a cryogenic low noise amplifier. Since the cryogenic amplifier has a lower input voltage capacity than the previous amplifier, the implementation will involve finding and testing a way to protect the amplifier through the use of a switch. The Thesis will also involve developing a design to hold the cryogenic amplifier in the cryostat apparatus, with considerations involving the amplifier's orientation, the capacity to move the amplifier to different regions of the apparatus, capability of temperature testing, and space for wiring. Deliberations on if the amplifier will affect the temperatures in the cryostat, how to test this, and if a heat load is necessary will also be taken into account. Once all of these tasks have been accomplished, testing on the amplification levels and the noise levels will be taken, determining the effectiveness of the project.

2 Background

2.1 Electron Spin Resonance

In order to understand the significance of a cryogenic amplifier in our apparatus, we must briefly discuss the method we use to interact with the Cr_7Mn spin sample: Electron Spin Resonance (ESR). This process is used to study materials with unpaired electrons and their spins. For some materials, these electrons can be quantum two-state systems that can act as a quantum bit (qubits). The qubits can have spin orientations of spin-up, spin-down, or superpositions of these states [3]. At temperatures around and below 3 Kelvin, Cr_7Mn is one of these materials. In order to interact with the sample, radio frequency (RF) pulses are generated through code written for a Quantum Instrumentation Control Kit (QICK). The RF pulses are then sent through an antenna, which connects to the loop gap resonator that interacts with the spins of the sample to elicit a response. Figure 2.1 shows two RF pulses that are sent in at specific times, their relative magnitudes, and the response's relative magnitude.

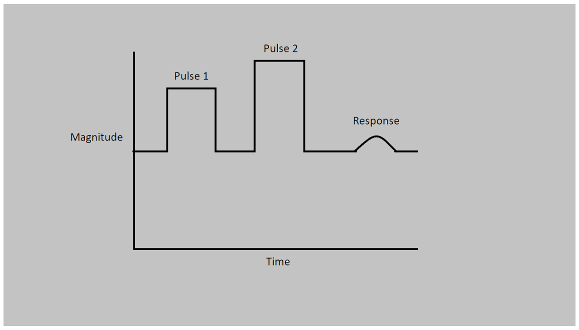


Figure 2.1: Pulses and Response (not to scale)

The response of the sample depends on variables such as duration, magnitude, and delay of the pulses, and the details of this can be found in Reference [4]. The response, as shown in Figure 2.1, is fairly small compared to the RF pulses that are sent. The response gives information on the sample and gives insight into how it can be used in quantum computing. The response is small enough that noise is a factor in analyzing the signal.

2.2 Electronic Noise

Noise is a term that can be used to describe the effect of random movements of electrons due to Brownian motion in electronic components, undesired signals, or any other disruptions in the background [2]. Those movements can cause fluctuations in voltage across the component that result in electronic or thermal noise. The thermal noise directly affects the temperature of that component. The thermal noise or noise temperature of a component is the power spectral density of the noise it produces in terms of temperature that would produce the same power density by thermal agitation [1].

Many electrical components can be represented as an ideal resistor in order to identify the relationship between the temperature of the component and the voltage, which determines the noise level. Starting with a rearrangement of Planck's black body radiation law, we can derive the noise temperature equation as follows from references [1] and [2]:

$$V_{rms} = \sqrt{\frac{4hF_c\Delta f R}{e^{hF_c/k_bT} - 1}}, \tag{1}$$

where h is planck's constant, k_b is boltzmann's constant, T is the temperature of the ideal resistor (noise temperature), R is the resistance of the component, F_c is the center frequency, and Δf is the bandwidth. An approximation of the denominator can be made assuming that microwave frequencies are used. With the first two terms of the Taylor series expansion of the denominator, the result is as follows:

$$\begin{aligned} e^{hF_c/k_bT} - 1 &= 1 + \frac{hF_c}{k_bT}\cdots \\ &= \frac{hF_c}{k_bT}. \end{aligned}$$

Substituting the new denominator into Equation 1:

$$V_{rms} = \sqrt{4k_bTR\Delta f}, \tag{2}$$

Equation 2 gives information about how the noise or magnitude of V_{rms} is proportional to the bandwidth. Over larger frequency ranges, the noise will be higher. Power spectral density, briefly mentioned above, is measured to analyze these noise levels over large bandwidths, and gives insight into the characteristics of the noise [1].

A way to compare the signal and the noise of a system is the signal to noise ratio (SNR). This ratio can be described using the noise figure, which quantifies how much a component degrades the signal to noise ratio. It accomplishes this by comparing the SNR without the component, then with the component. An ideal component has a noise figure of 0, but all components degrade the SNR by some degree [5].

Finally, using Equation 2, solving for temperature and substituting the noise power P in for V_{rms}^2/R, we get:

$$T = \frac{P}{4k_b \Delta f}. \tag{3}$$

Equation 3 shows the relationship of noise temperature to the noise power. It also gives a way to calculate and directly compare the noise temperatures of given components over certain frequency ranges, which shows similar information to the noise figure. A component giving off a certain noise temperature has the same power spectral density as an ideal resistor operating at the equivalent component temperature. This is useful for our apparatus because it follows that components at extremely low temperatures ($\approx$ 5K in this case) will have low noise levels when compared to similar components at room temperatures. Though there are many different methods to reduce noise levels, such as signal analysis in post processing, filtering unwanted frequencies, shielding, improving circuit design, or reselecting components, since our apparatus has a capacity to put components at low temperatures, it is advantageous to use the space and implement a cryogenic amplifier.

2.3 Cryogenic Amplifiers

Amplifiers are effective at taking a signal that is relatively small and making that signal larger at the output. For some background we'll look at a common-source FET amplifier, which is an idealistic model of more complicated amplifiers, and will provide some knowledge of how cryogenic amplifiers work. The diagram in Figure 2.2 shows the common source FET amplifier [6]. This type of amplifier uses a transistor (an NFET in this case) as a valve that takes the input signal V_{in} which controls whether the drain source current I_{DS} over the resistor R_D flows from the power supply $+V$ to ground. The output signal V_{out} is taken between the NFET and the drain resistor and has a larger signal than V_{in} [6].

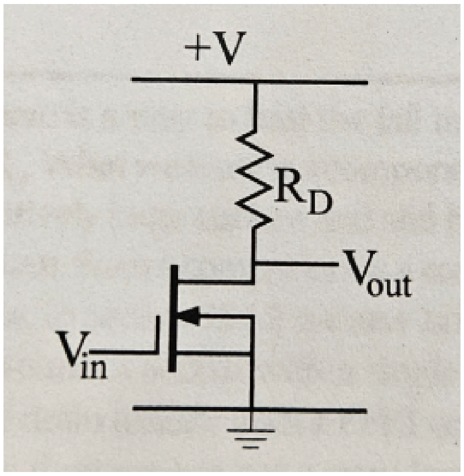


Figure 2.2: Common Source FET Amplifier, Taken from Reference [6].

For our experiment, amplifiers are necessary due to the small signals that we receive from the ESR samples. Previously, we have used room temperature low noise amplifiers, which are capable of amplifying the response signal with a relatively low noise figure and signal to noise ratio. However, since they are at room temperature, the noise power of those components is higher relative to the signal power, and thus has a lower signal to noise ratio than an amplifier at low temperatures. With the implementation of a cryogenic amplifier, it is possible to greatly improve the signal to noise ratio, resulting in a clearer picture of the response from our sample. Since the sample, the cryogenic amplifier, and the connectors will all be around 3-5K, electrons at this temperature have a much lower level of kinetic energy. The random motion of these particles will be slower, leading to a lower power spectral density which results in a smaller noise temperature, as seen in Equation 3.

Cryogenic amplifiers operate similarly to common source amplifiers, but the materials used are different, and requires a more intensive design process. When building a component that must be operational in the low Kelvin range, thermal contraction becomes an essential part of the design process. For some manufactured materials, they are specifically designed to have extremely small contraction coefficients, and any contraction will be basically negligible. For other materials, thermal contraction occurs when they are cooled down, and tend to shrink. This is normal and occurs in small amounts at temperatures we see in daily life. When cooling from room temperature to the low Kelvin range, many materials have significant thermal contraction, but materials used for these purposes are carefully chosen: metals used for low Kelvin temperatures contract about 0.2 - 0.4%, while other materials, like organic materials used for insulation, bonding, or leak tight joints, contract about 1-2% from their size at room temperature [7]. With specially picked materials and alloys, cryogenic amplifiers are built to manage the thermal contraction. However, the cryogenic amplifier has a different limitation that requires a switch in order to protect it.

2.4 Switches

An important aspect of the use of amplifiers is the need to protect the amplifier. The pulses that are sent in to the cryostat to elicit a response from the sample are much larger than the resulting response. Large enough, that if the cryogenic amplifier received these pulses, it would permanently damage the amplifier. For the previous room temperature amplifier, this wasn't an issue because the input limits were higher than the input pulses. In order to prevent the cryogenic amplifier from being damaged, it is necessary to control when the signal opens to the amplifier. There are many different ways to do this, such as using a directional coupler with a limiter, but as Toby Weissman determined in his undergraduate thesis, a switch is the simplest method to do this [1].

There are many different types of switches in electronics, but we'll focus on one: the single pole double throw (SPDT) switch. Figure 2.3 shows a diagram of this switch and the important terminology associated with it.

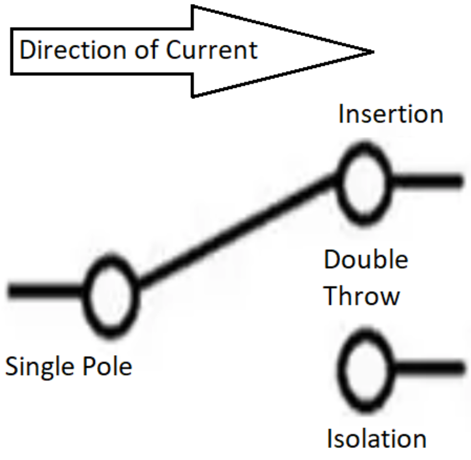


Figure 2.3: Diagram of a Single Pole Double Throw Switch

In Figure 2.3, the throw that the switch is connected to is considered the insertion side, where the switch is on. The throw that isn't connected is called the isolation side, where the switch is off. An indicator of a switch's quality comes when measuring the level of insertion loss, or how much a voltage drops over the switch when it is on. A low insertion loss means higher quality. On the other side, a measure of the isolation voltage shows how well the switch blocks the current from flowing when it is off. A high isolation level shows higher quality.

The switch protects the amplifier by switching at the right time. When the pulses are sent in to the cryostat, they have to pass through the switch's insertion side and interact with the sample, causing a response. The pulses will reflect off the isolation side, and travel back towards the input. The response will follow the pulses unless we time it so that the switch goes to the other throw right before the response gets to it. That way, only the response is traveling through the amplifier, and not the pulses. More about how this is done is discussed in Section 4.1.

2.5 Heat Loads

Another aspect of this project requires an understanding of cooling power. Throughout the project, it remained a question as to whether the cryogenic amplifier would cause heating in the cryostat, and if so, how much heating it would cause. As will be discussed in Section 3.1, the cryostat has different cooling stages, with varying temperatures at each stage. Work was done by Toby Weissman to measure the temperatures at these stages, seen in Reference [1]. Mentioned in Section 2.3, placing the amplifier where it is the coldest (as long as it's above 3 Kelvin) produces the best noise figure. So, placing the amplifier in the lowest cooling stage, which is where the sample is, is more ideal. This means that it became necessary to see how much heating the lowest cooling stage would receive by the amplifier, and if that would have a negative effect on the sample and it's response. Luckily, there is an easy way to test this, by doing an experiment with the amplifier in the lowest stage, cooling it down, and measuring the temperature of both the amplifier and the sample area when the amplifier is off and when it is on and receiving signals. This experiment is discussed in detail in Section 4.

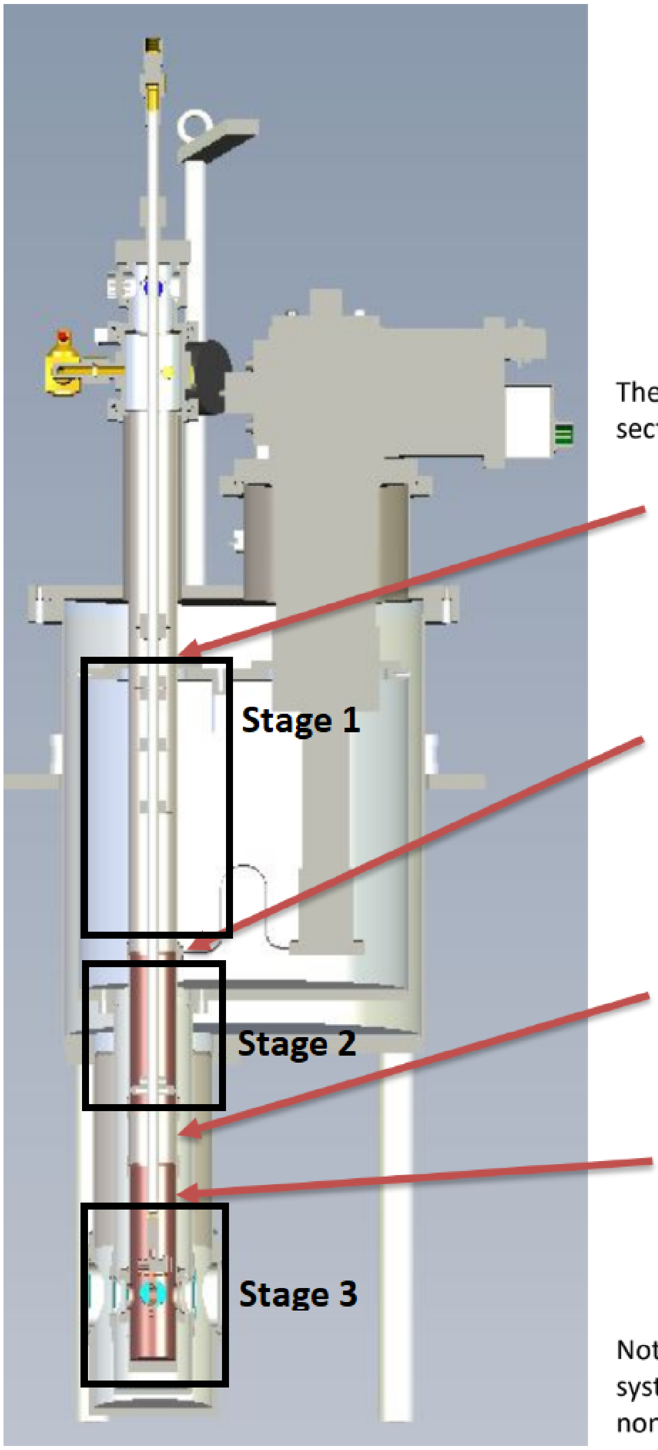
In the scenario where the heating by the amplifier is significant enough, a heat load or a thermal connection to a cold bank (the cryostat) is required. For more information regarding thermal conductivity of various materials used for this project, such as Helium, copper, stainless steel, and how to maximize that conductivity to minimize any heating caused by the amplifier, see Matter and Methods at Low Temperatures, written by Frank Pobell [7].

3 Apparatus

As this project was primarily an engineering process, the apparatuses in this section have important and detailed descriptions. Some considerations as to the design process and solutions to specific problems will also be discussed. The setups of experiments will be briefly described in Section 4 for each experiment pertinent to the project.

3.1 Cryostat Apparatus

The cryostat used in this experiment is the Janis model SHI-950. The cryostat uses condensed helium to cool the cryochamber down to around 3 Kelvin. The most important piece of this apparatus is the three different cooling stages, outlined in Figure 3.1: The first stage, which provides thermal isolation from room temperature; the second stage, which uses OFHC Copper (a useful form of copper ideal for thermal conductivity) that allows for further cooling; Another stainless steel thermal isolator; and finally, the third stage, where the helium is condensed to liquid form and where the sample is. This final stage is where we will place the cryoamplifier. For more information on the work done to determine the temperatures corresponding to these three stages, see Reference [1].



The sample tube consists of three sections:

1) Stainless Steel top section for thermal isolation of sample area from room-temperature with thermal anchor to 1st stage radiation shield.
2) Transition to OFHC Copper section with thermal anchor to 2nd stage of cold head.
3) Transition to Stainless Steel thermal isolator
4) Transition to OFHC Copper sample zone for condensing LHe and operating to T<1.5K.

Note: This drawing shows an optical system. The operation is the same for non-optical systems.

Figure 3.1: Cryostat Apparatus, Taken from Reference [8]

Access to any of the stages requires a Tube Apparatus that can be taken out from the top of the cryostat. Figure 3.2 shows a picture of the tubing that we use to access these stages. As marked in the Figure, there are baffle regions outlined by the green baffles. These baffles can slide along the G10 rods, and vary from experiment to experiment, but in Figure 3.2, baffle region 5 roughly lines up with cold stage 3 in Figure 3.1, baffle region 4 lines up with cold stage 2, and baffle region 3 lines up with cold stage 1. Baffle regions 1 and 2 are above the cold stages, and the baffles simply allow for control of wiring and provide stability in the structure.

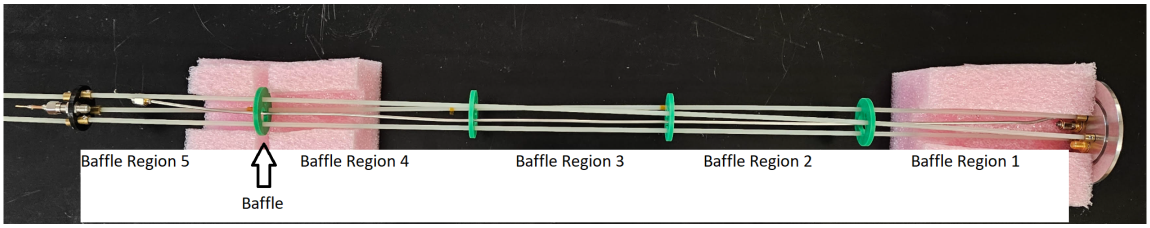


Figure 3.2: Tube Apparatus with Baffle Regions

3.2 The Cryogenic Amplifier and its Holder

The amplifier that was chosen to be implemented into the cryostat is the LNF-LNC0.3_14B, a low noise amplifier from the Low Noise Factory. This amplifier is designed to work well in temperatures above 3 Kelvin, and provides amplification of around 37 dB in ideal conditions. It has standard SMA connectors and a Nano-D connector to provide power [9]. Figure 3.3 shows the dimensions of the amplifier, which were necessary in designing the holder.

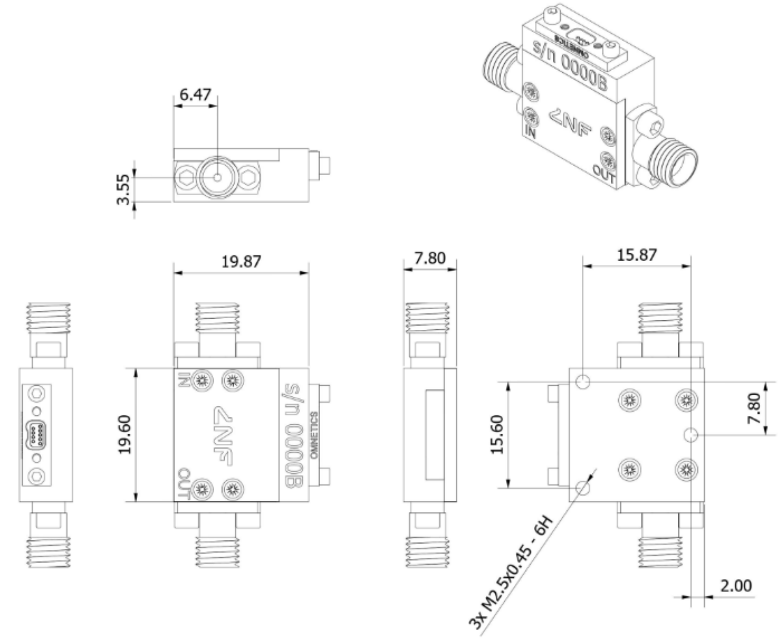


Figure 3.3: Dimensions of Cryoamplifier, Units in millimeters, Taken from Reference [9].

There were multiple factors that went into the design of the amplifier holder. Considerations included how the amplifier would be oriented, how it would be held in place, and as discussed in Section 2.5, whether or not it would need to absorb any heat from the amplifier. Regardless, we needed to test the amplifier in the cryostat before any determination about heat loads could be made, which required some form of temporary holder. Shown in Figure 3.4 is a picture of the Fusion 360 design of the baffles that stabilize the G10 rods in Figure 3.2. This is the design that was altered to hold the cryoamplifier.

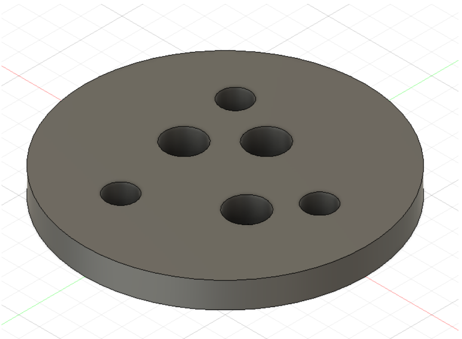
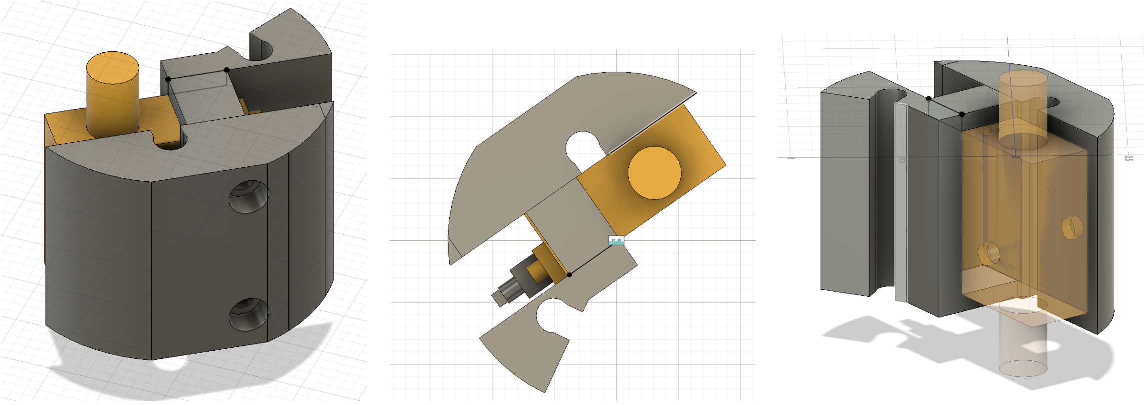


Figure 3.4: Baffle used for the Tube apparatus

The three smaller outermost holes correspond to the three G10 rods used to stabilize the system, and the 3 larger innermost holes correspond to the ingoing and outgoing SMA cables and the dialectric that controls the antenna. The amplifier had to fit in and around all of this, though there was some flexibility in each component being able to move a little to accommodate.

Figure 3.5 shows multiple views of the Amplifier (in yellow) and the final design of the holder (in gray) that was used to keep the amplifier in place. The holes in Figure 3.5a are where screws go to hold the amplifier, while the two slits shown in Figure 3.5b are where the G10 rods slide into place. The design also allows ample room for the wire leads that power the amplifier to come up through the Tube Apparatus without getting caught or stuck on any other parts. It can also be snapped on to any baffle region before use, allowing us to test the amplifier in any of the cold stages.



(a) View 1 (b) View 2 (c) View 3

Figure 3.5: Cryoamplifier and Holder with Different Views

The final design of the Cryoholder was 3D printed, and Figure 3.6 shows the overall placement of the amplifier in relation to the Tube Apparatus, as well as the T connector on the right side.

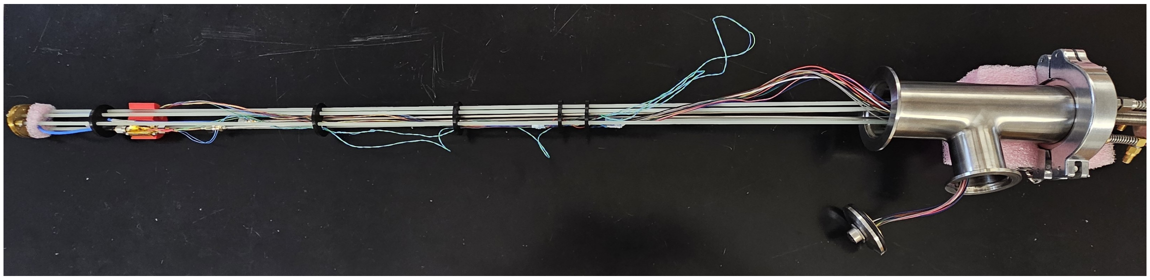
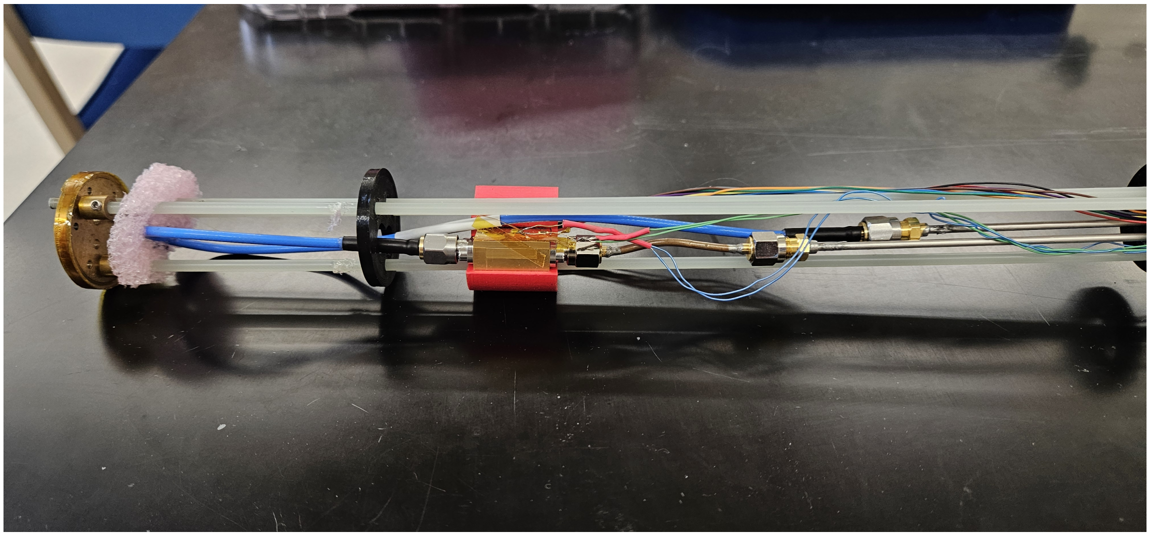
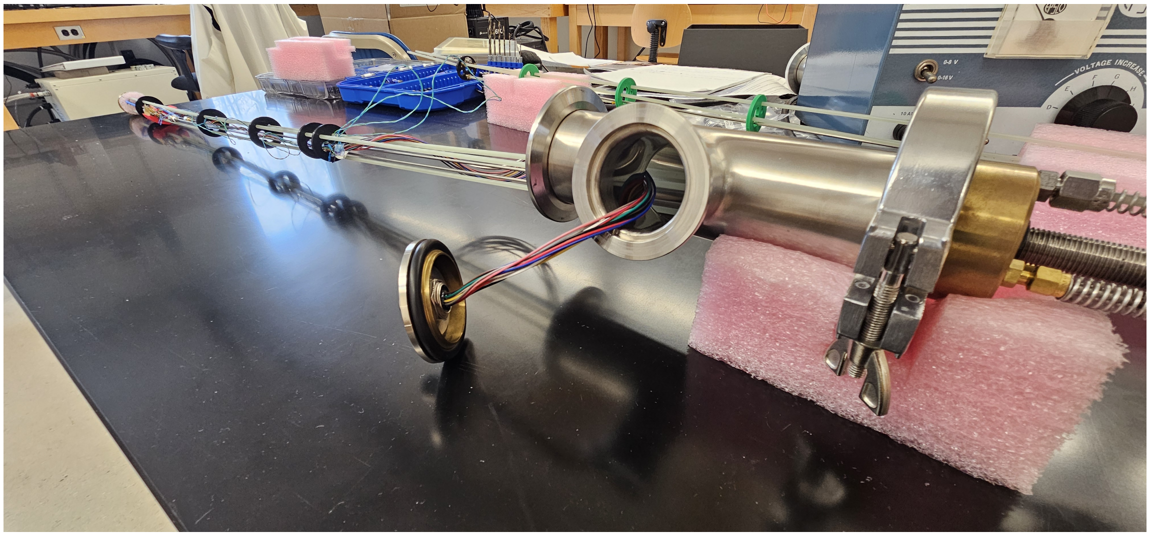


Figure 3.6: Tube Apparatus with The Cryogenic Amplifier and Wiring

Figure 3.7 gives a closer view of either end of the Tube Apparatus. Figure 3.7a shows the cryoamplifier, the holder in red, the thermistor taped to it, and the SMA connectors on either side. Figure 3.7b shows the T-intersection in reference to the rest of the apparatus, and also shows how the wiring was done through the KF-40 Flange. Both Figures 3.6 and 3.7 show the set up of the experiment that will be discussed in Section 4.2.



(a) Cryoamplifier with Thermistor

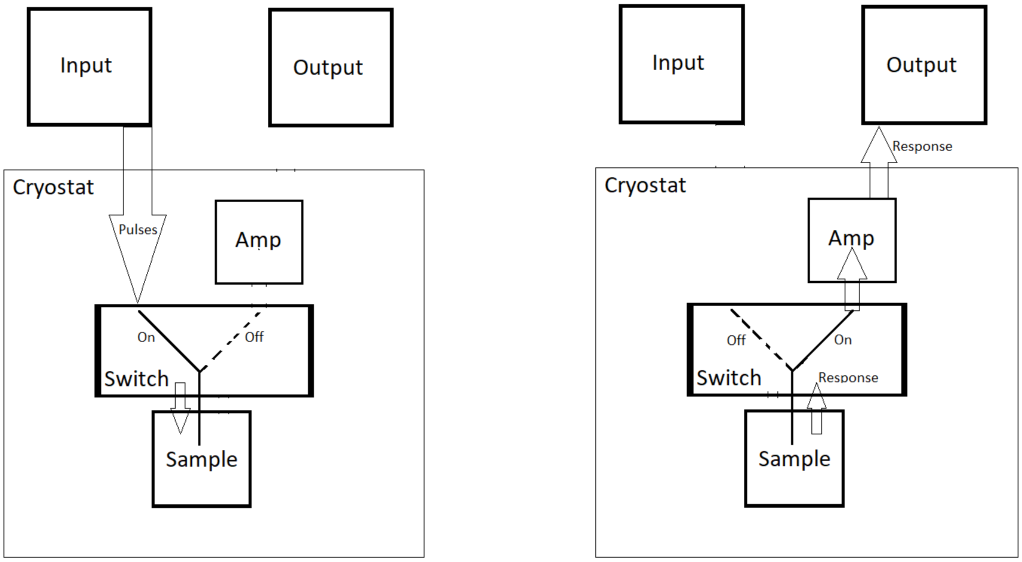


(b) T-Intersection View

Figure 3.7: Experimental Tube Apparatus

3.3 Switch Apparatus

Figure 3.8 is a diagram that theoretically shows where the switch should be in our apparatus. It also shows how the switch works to block the pulses from entering the amplifier, and only letting the response enter. Figure 3.8a shows the path of the pulses, and the switch will stay at that orientation for long enough that the pulses will be reflected back to the input, but not long enough for the response to reflect back as well. Figure 3.8b shows the result of an accurate timing of the switch, with only the response being amplified and getting back to the output.



(a) Switch Position with Pulses (b) Switch position with response

Figure 3.8: Theoretical Switch Placement

The switch used in the experiment described in Section 4.1 is the MMIC SPDT Non-Reflective Switch, and is shown in Figure 3.9. It is important to note that this switch is not compatible with the cryostat apparatus, it is too large and will not fit. However, the switch that we will be acquiring, which is designed by students at Amherst, acts in a very similar manner and our experiments and testing is similar as a result. This new switch has also been tested in low Kelvin temperatures by groups at Amherst College, so it shouldn't be an issue for our experiment.

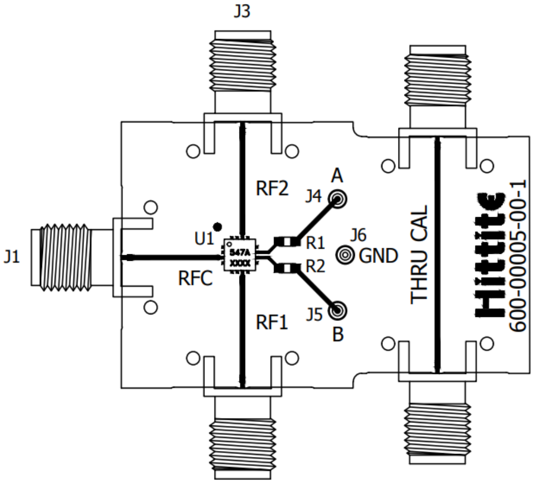


Figure 3.9: Switch Circuit

4 Methods

4.1 Switch Testing

This section goes over how to set up the switch using the QICK and using a Jupyter Notebook to run a Carr-Purcell sequence on the QICK. Other experiments were done in order to test the switch's effectiveness, such as measuring the insertion loss and isolation, the results of which will be discussed in Section 5.1.

4.1.1 Switch Set Up

As mentioned in Section 3.3, the switch used for this experiment is shown in Figure 3.9. Figure 4.1 shows where the connectors on the QICK are to set up the switch. To control the switch with the QICK, pins A and B on the switch circuit are connected to pins 0 and 1 on the QICK, by the switch control box in the Figure. Other pins on the QICK in this box can be used as well. In order to send signals to the switch, the J1 SMA connector must be connected to the QICK by the signal processing box, with either port DAC_A or port DAC_B. To receive the resulting signal, the RF1 or the RF2 port must be connected to either the ADC_C or the ADC_D on the QICK, by the Signal Processing box in the Figure.

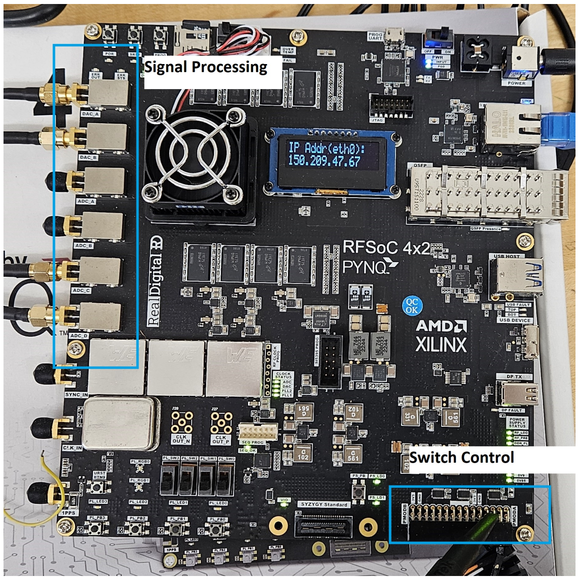


Figure 4.1: QICK Control Board

4.1.2 Carr-Purcell Sequence

We can use the QICK to run a Carr-Purcell Sequence. This sequence sends two pulses, and simulates a response, which would be similar to an actual test of a sample. It is like the Hahn echo experiment, except the Carr-Purcell Sequence continuously sends these pulses and the response at a certain frequency, whereas the Hahn Echo experiment only does the pulses once. For our purposes, it is easier to test the switch with the simulated Carr-Purcell Sequence, as we can run that continuously while changing certain parameters and analyzing the results.

4.1.3 Testing the Timing

In order to test the timing of the switch, some parameters in the code had to be added and redefined. For our purposes, we need the switch to alternate shortly after the second pulse of the Carr-Purcell Sequence, ensuring that the response is seen by the amplifier and not the pulses. Both the *offset* variable and the *myvar* variable are responsible for this timing. While *myvar* is simply an adjustable timing parameter and is not defined by any other variables, *offset* has a very specific definition that had to be altered in order to achieve the correct timing. The following definitions show how *offset* was previously defined, and how it was changed to be functional.

Previous Definition:

$$\text{Offset} = 0 \text{ if self.cfg[''loopback'']}$$

$$\text{else Offset} = \text{(delay)}\,\text{[tpi2 + delay + self.cfg[''pulses'']*tpi]}$$
$$+ (2 * \text{self.cfg[''pulses'']} - 1)$$

Functional Definition:

$$\text{Offset} = 0 \text{ if self.cfg[''loopback'']}$$

$$\text{else Offset} = \frac{\text{tpi}}{2} * [\text{tpi2} + \text{self.cfg[''pulses'']}]$$
$$+ (2 * \text{self.cfg[''pulses'']} - 1)\,\text{(delay)}$$

There were some errors in the previous definition of *offset*that are simply typos, but the main difference besides that is the previous definition tried to calculate when the response would be, not when the second pulse would end. The functional definition instead uses the length of the pulses, the number of pulses sent, and the delay time to determine when the final pulse is done, right after tpi2 and before the response in Figure 4.2.

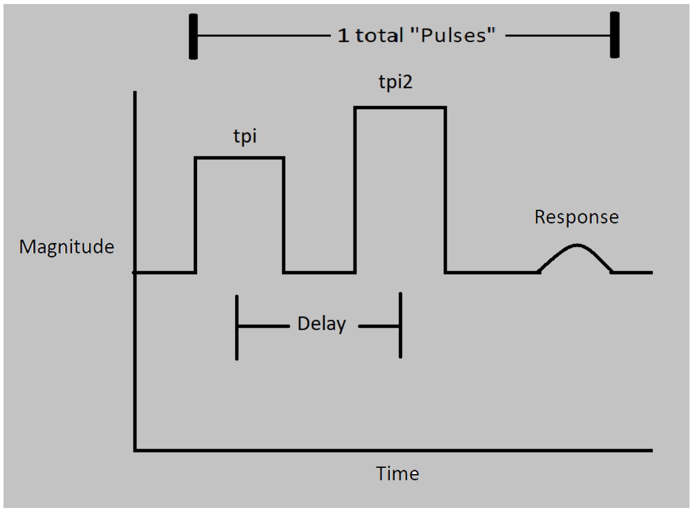


Figure 4.2: Timeline showing Different Variables defined in Table 1

delay	Delay time between median of first and second pulses
tpi	The time of the first pulse in cycles
tpi2	The time of the second pulse in cycles
self.cfg[”pulses”]	The number of times tpi and tpi2 are sent in

Table 1: Reference Variables (See Figure 4.2 for a picture of these variables)

Table 1 shows the variables within the definitions, and Figure 4.2 shows how these definitions are related to each other. The cycles in Table 1 refer to the inner clock system that the QICK has built in. This allows better control than if we were to use a server-like setup through Jupyter Notebook, as that depends on the quality of the network connection and can have delays significant enough to change what we are trying to test.

Overall, *offset*, like *myvar*, is part of defining when the switch actually triggers. *myvar* accounts for other delays in the system, such as different length wiring, that the *offset* variable can't account for. The experiment was to change *myvar* so that the triggering of the switch is at the right time, and the results of this are seen in Section 5.1.

4.2 Amplifier Testing

Testing the Amplifier to ensure that it meets the specifications outlined in Reference [9] requires testing at both room temperature and at low Kelvin Temperatures. For our apparatus, we needed to acquire some additional materials in order to use the cryogenic amplifier that we purchased. These items, recommended for use with our amplifier, include the LNF-PBA, which is a Low Noise Power Block, the LNF-PS3B, which is the Low Noise HEMT Power Supply, and the specific bulkhead connectors and other wires needed to use these devices. The following sections walk through how to use these devices, safety considerations, any soldering required, and finally testing the amplifier.

4.2.1 Room Temperature: Soldering

In order to power the amplifier, soldering certain connections is required. Table 2 shows the soldering connections that need to be made according to the wire color, the pin number, and the type of connection.

Once soldering is complete, the amplifier can be powered using the LNF-PBA and the LNF-PS3B. Before use of these devices, review of the data sheets for each

Connection Type	LNA Wire Color	M12 DC-Out Color	M12 DC-Out Pin Number
Drain Voltage (V_{ds})	Orange	Black	1
Gate-Source Voltage (V_{gs})	Yellow	Orange	4
Ground	Red	Yellow	5

Table 2: Soldering connections for room-temperature testing

is necessary. The LNF-PBA datasheet is Reference [10], and the LNF-PS3B is Reference [11]. The following section shows how to set the system up correctly for first and subsequent uses.

4.2.2 Setting Up The Power

Start with the power block (LNF-PBA). This device must be on a flat surface, with the vents uncovered. Connection to the mains must be made with cord compatible with IEC 60320-C14 with an earth prong to allow for ground connection. Each output connector on the device provides ±12 VDC needed for the power supply (LNF-PS3B). It is important that the current does not exceed 1700mA. If it does, permanent damage could occur to the power supply. Make sure all devices are switched off. Connect the power block to mains, and then connect the power supply to the power block using the LNF-CAB_PBA_PS3b cable. Set the power block to non-floating mode by putting in the jumper plug. Then, switch on both the power block and the power supply. Set the V_{ds} to the nominal value of 1 Volt using the trim potentiometer. This ensures that when connecting to the amplifier, the values are well within the range of capacity for the amplifier. Before plugging in the amplifier, turn off both the power supply and the power block.

At this point it is safe to connect the cryogenic amplifier to the power supply using the M12 DC-Out cord that we soldered, which connects directly to the cryoamplifier wire leads. Then, turn on the power block and power supply, and check that the measured I_{ds} does not exceed the max value in the datasheet (100mA). This value can also be adjusted by a trim potentiometer on the power supply.

After carefully following the procedure outlined above, the cryoamplifier can be tested. When the system needs to be turned off, make sure the jumper plug is installed on the power block, then simply turn off the power supply and the power block, and disconnect the amplifier from the power supply. To turn the system back on again, a much simpler procedure of connecting the amplifier back to the power supply and turning on both the power supply and the power block is sufficient.

4.2.3 Room Temperature: Testing the System

Now that the system is set up, we can test the amplifier's noise and gain levels and compare them to the measured data from the amplifier's datasheet [9]. Using a Vector Network Analyzer (VNA) to send a signal to the amplifier, and a Spectrum Analyzer to receive the signal from the amplifier, we can directly measure the gain and the noise levels. The main importance here is to make sure to use at least 30dB of attenuators attached to the VNA, to ensure that the amplifier doesn't get a signal too large. For our purposes, we used 50dB of attenuation. Next, we can measure the signal from the VNA to the Spectrum analyzer without the amplifier, and compare the two gains to get a measure of amplification, and to cross check the results with the expected data from the datasheet.

4.2.4 Low Kelvin Temperature: Soldering and Power Setup

Testing at low temperatures is a bit more involved, and requires more solder connections and wiring to accommodate for the cryostat, the thermistor attachment, and the bulkhead connector (M12A-12PFFS-SH8C50) that goes through the Flange attached to the T intersection. Table 3 shows all the solder points made for this experiment, as well as the thermistor that connects to the amplifier.

Device	Connection Type	Wire Connector from Device	Bulkhead Pin #	Bulkhead Color	M12 DC-Out Pin #	M12 DC-Out Color
Cryo Amp	V_{ds}	Orange	1	White	1	Black
Cryo Amp	V_{gs}	Yellow	2	Brown	4	Orange
Cryo Amp	Ground	Red	3	Green	5	Yellow
Thermistor		Green 1	4	Yellow		
Thermistor		Blue 1	5	Gray		
Thermistor		Green 2	6	Pink		
Thermistor		Blue 2	7	Blue		

Table 3: Cryogenic Wiring and Bulkhead pin assignments

Once the new soldering connections are made, the remaining procedure involves setting up the Amplifier with the holder and the thermistor on the Tube Apparatus, as seen in Figures 3.6 and 3.7. This can be done by first snapping the holder onto the G10 rods in the desired baffle region and threading the wires through the baffles down to the holder. The thermistor is then taped onto the amplifier, making sure that the metal leads on the thermistor won't make contact with the amplifier or the cryostat by putting Kapton tape on the amplifier itself. Then, the amplifier slides into the holder with the correct orientation. The SMA cables connect to the amplifier, and the amplifier is then screwed in to the holder, while the amplifier connector is screwed into the amplifier. After all this is done and checked, the Tube Apparatus can be slid into the Cryostat, where a pressure check is done to make sure the bulkhead connector that is attached to the flange is leak proof. Finally, the cryostat can be cooled down, and the same test outlined in Section 4.2.3 can be done here, as long as the procedure from Section 4.2.2 is done correctly.

5 Results and Discussion

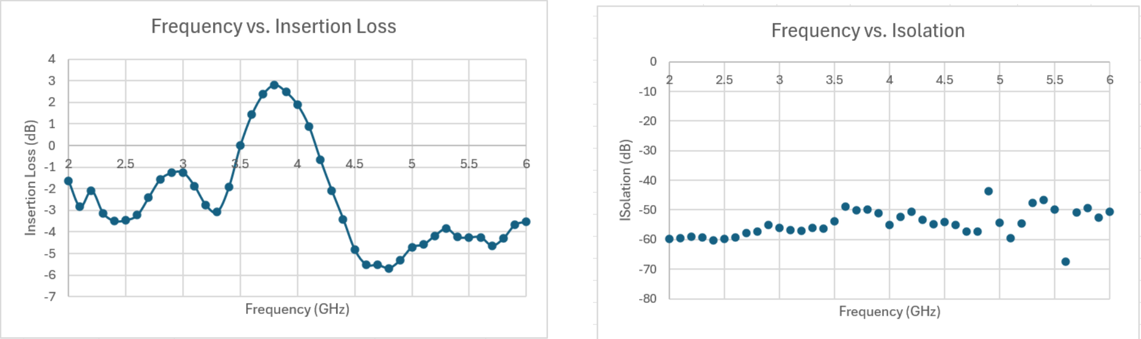
The results of both the switch experiments and the Amplifier experiments are outlined in the following sections. The implications of these results and the next steps are also discussed after each experiment.

5.1 Switch Testing Results

The results from the following tests are adequate for the system at hand, though it must be noted that this switch is not the one that will be used with the cryogenic amplifier. These tests should be redone with the new switch that fits in the system.

5.1.1 Isolation and Insertion Loss

The results of testing the gain levels over the isolation and the insertion side of the switch are shown in Figure 5.1, and are acquired using the VNA and Spectrum analyzer in a similar setup to the QICK set up.

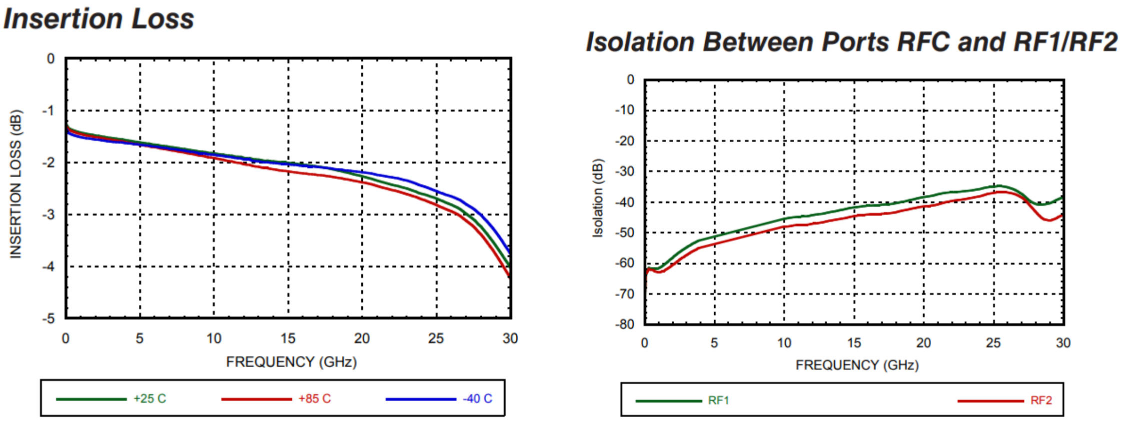


(a) Insertion Measurements

(b) Isolation Measurements

Figure 5.1: Insertion and Isolation measurements

The Isolation measurements from Figure 5.1b provide the expected results when compared to the expected results from the data sheet, shown in Figure 5.2, with the isolation levels around -55dB for the range of 2 to 6 GHz. However, the Insertion loss differs slightly from the expected results, as seen in Figure 5.2a, with a notable jump above 0dB right around 4GHz, something lacking in the expected graph. For some reason, around this frequency the switch added to the signal instead of took away from it. This could be due to slight wiring issues, and would be worth doing further testing if we were to use this switch in concert with the Cryogenic amplifier. However, since we plan on using a different one, it is better to test that switch to ensure it doesn't have any issues instead.



(a) Expected Insertion Loss (b) Expected Isolation Levels

Figure 5.2: Insertion Loss and Isolation levels of Switch, Taken from Reference [12].

5.1.2 Conversions of Power Measurements

The results that are received by the QICK when the switch is connected to it (as outlined in Section 4.1) are in the form of an arbitrary unit (a.u.). We must be able to translate this unit to a recognizable form of power. Thus, another test was done to find the conversion between dBm's and a.u.'s. Note that a dBm measures an exact power level, where as a dB is a relative measurement that gives a change in the power level. The test involved setting an arbitrary gain level in the QICK code (anywhere from Gain=0 to Gain=32500, which is the maximum), finding the magnitude of that output signal from the QICK code, and measuring it with the spectrum analyzer. Figure 5.3 shows the results of the input gain in a.u.'s to the output in dBm's.

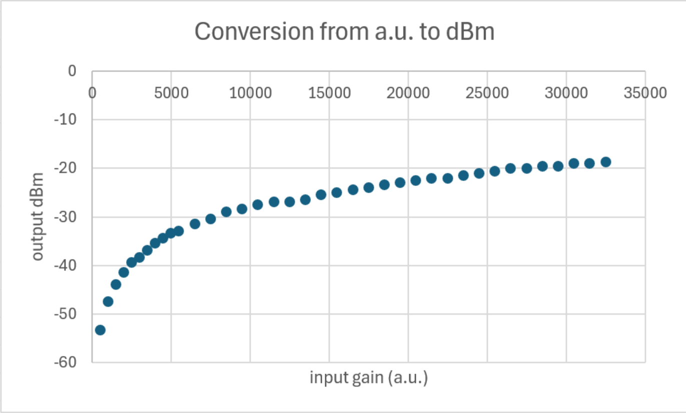


Figure 5.3: Conversion from a.u. to dBm

The second part of the conversion is using the QICK to run the test and give a value for the magnitude of the pulses received (instead of the magnitude of the pulse that we choose). Figure 5.4 shows the results of that test, where the magnitude value correlates to a certain output in dBm's. This allows us to know what the magnitude of the response is without having to use the spectrum analyzer every time, as well as the magnitude of the pulses we send in. Also shown in the Figure is the equation that converts the values.

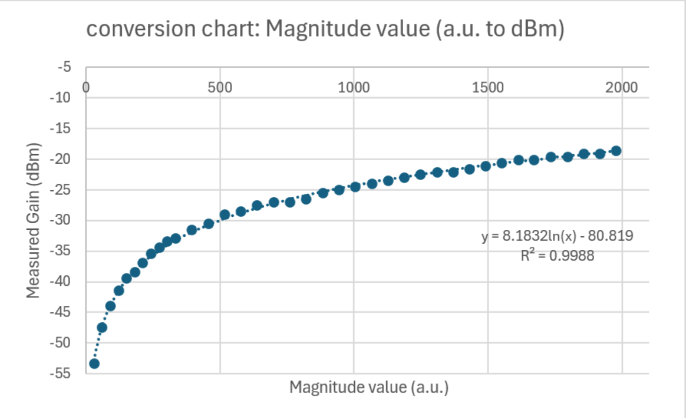


Figure 5.4: Output read from the QICK

Figure 5.4 tells us that as the magnitude of the response gets smaller, the power of that response decreases exponentially once it is below around 250 a.u.'s. We believe the nonlinearity is due to some internal coding in the QICK that is yet to be fully understood. While not a critical issue, it is important to note this so that if any tests done using the QICK show some odd trends around these magnitudes, it may be a result of this nonlinearity.

5.1.3 Offset Testing

One of the most important aspects of testing the switch is making sure that we control when it switches so that we can protect the amplifier. Using the code for the Carr-Purcell Sequence and other factors outlined in Section 4.1, we get the following graph in Figure 5.5.

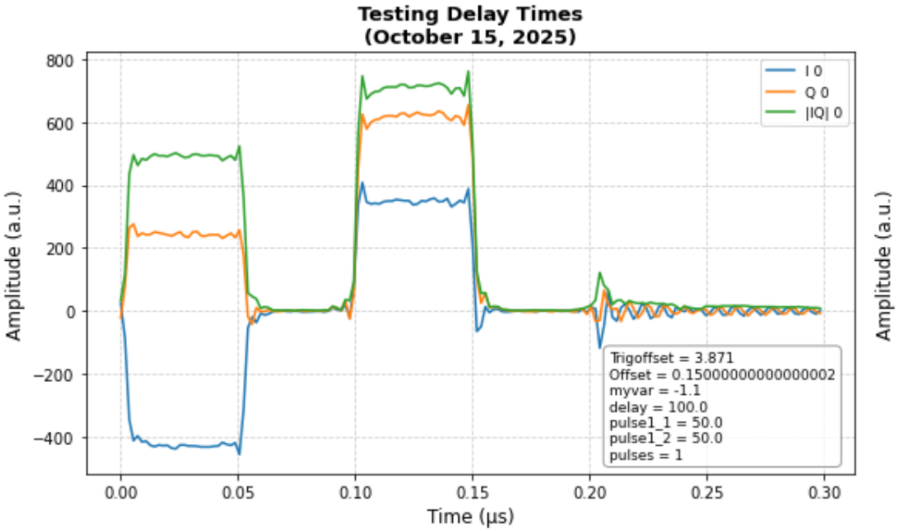
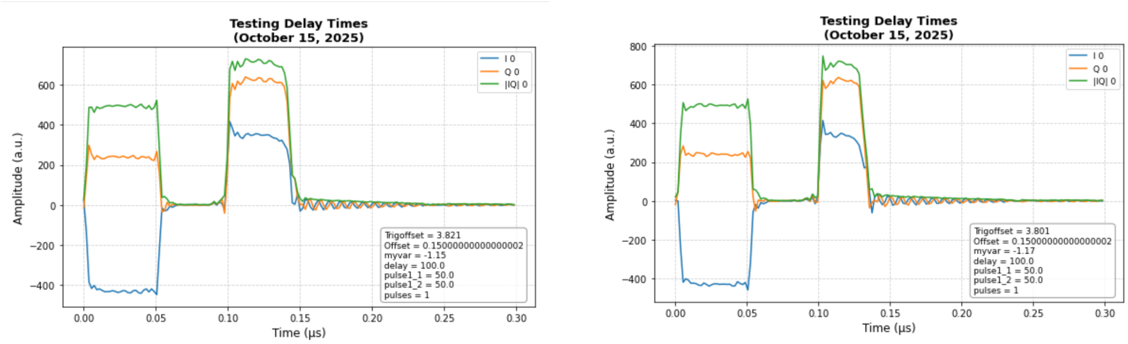


Figure 5.5: Sample Graph of Carr-Purcell Sequence

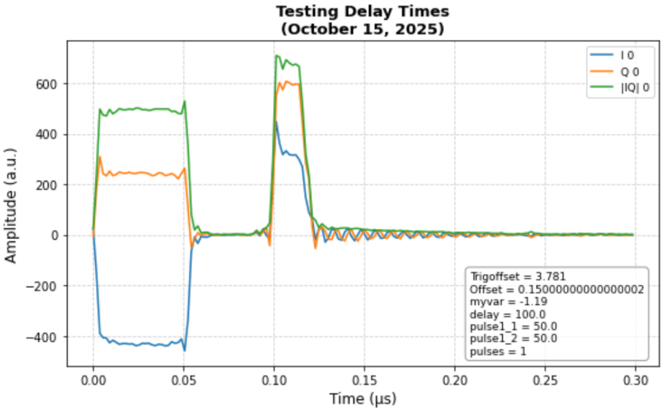
Note that the main focus is on the green line, which just shows the magnitude of the pulses. The other lines are unimportant for our purposes, and the blip around 0.20 microseconds is just some noise from the switch triggering. For this graph, the *myvar* variable is -1.1, which is not enough to cut into the 2nd pulse. However, we don't know exactly how far it is away from that pulse. So, further tweaking is required to see when the *myvar* variable changes enough so that the switch triggers where we can see it cut into the pulse. Then, we can plan accordingly and account for it to be right after the pulse. Figure 5.6 shows this in action, with the 2nd pulse getting a bit shorter each time *myvar* becomes more negative.

Though these results allow us to select *myvar* so that the switch triggers after the second pulse, there are some discrepancies when running the test with a constant *myvar* = -1.15. Figure 5.7 shows how much variation occurs.



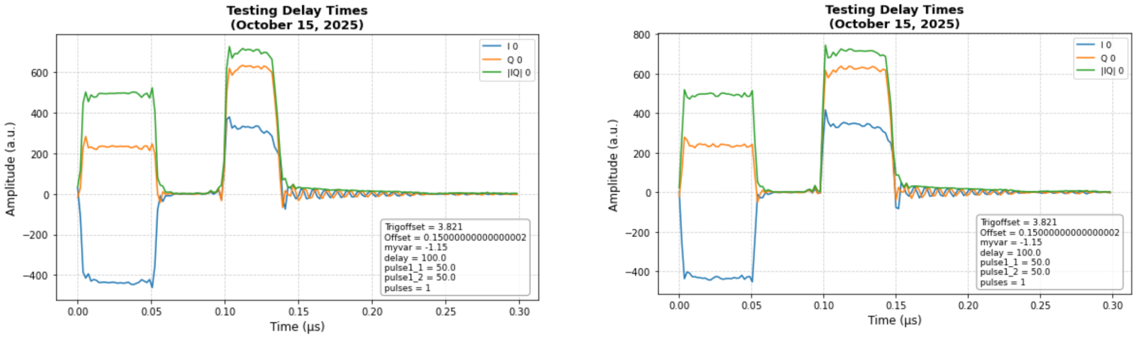
(a) $Myvar = 1.15$

(b) $Myvar = 1.17$



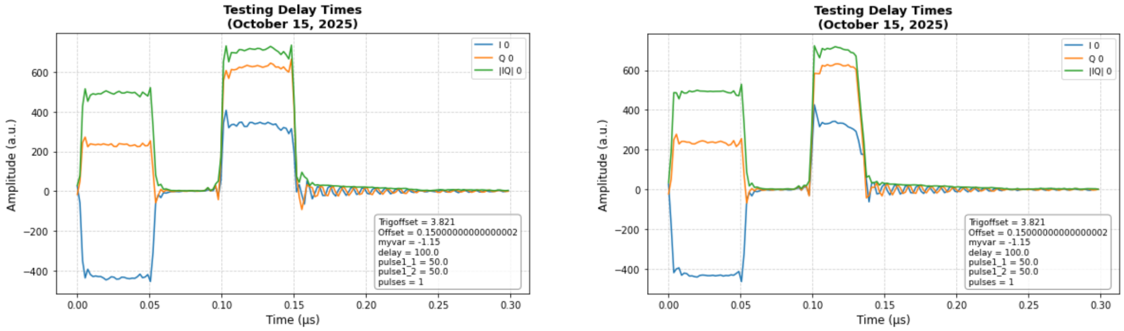
(c) $Myvar = 1.19$

Figure 5.6: Differing *Myvar* times



(a) Delay discrepancy 1

(b) Delay discrepancy 2



(c) Delay discrepancy 3

(d) Delay discrepancy 4

Figure 5.7: Measured delay discrepancies

Accounting for this discrepancy in the timing will involve another test with a real sample, loop gap resonator, and switch, which can be done at room temperature. When something starts resonating from a pulse, and then that pulse stops, the resonator effectively has a ringdown, similar to a bell being struck. The ringdown is the section where the signal exponentially decays from the maximum power to rest. The test will be making sure that the switch triggers after most of the ringdown has occurred so that whatever signal is left when the amplifier receives it is low enough to not damage the amplifier. The discrepancies in the timing simply mean that we will have to account for a larger margin of error, with roughly 0.2 microseconds of variation.

5.2 Amplification Results

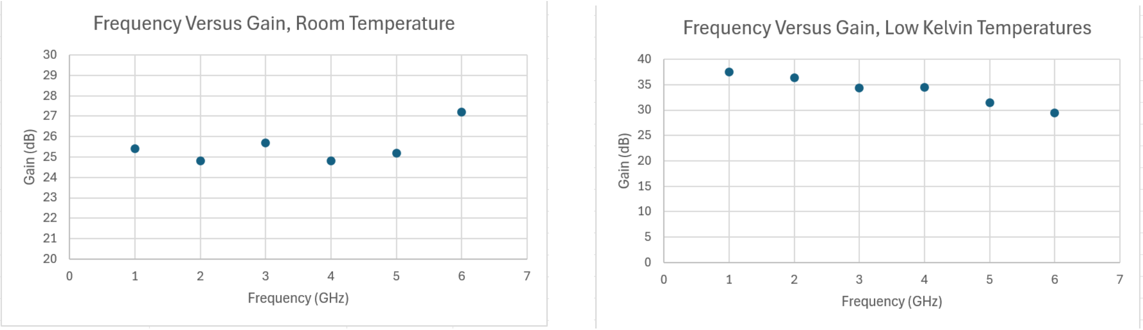
The results in the following sections are from the experiments outlined in Section 4.2. They show both the amplification from the cryoamplifier at room temperature and at cryogenic temperatures. The parameters shown in Table 4 are for both the room and low kelvin temperature test. The expected results from the Cryogenic amplifier data sheet are also shown with a discussion on any discrepancies [9].

Parameters	Value
Attenuation (dB)	50
Drain Voltage V_{ds}	1.002
Drain Current I_{ds}	10.19

Table 4: Parameters for Amplifier Tests

5.2.1 Room Temperature and Low Kelvin Temperature

Figure 5.8 Shows the Room Temperature and the Low Kelvin temperature amplifier tests, and the associated gain for the given frequency. The limit for our tests were from 0 to 6 GHz because the Spectrum Analyzer and the VNA are only capable of going up to 6 GHz. Past that, they start to have more trouble picking up signals. For our purposes, we are mostly testing samples in this range. If more testing is needed, there are also other ways to test other frequencies using the QICK.

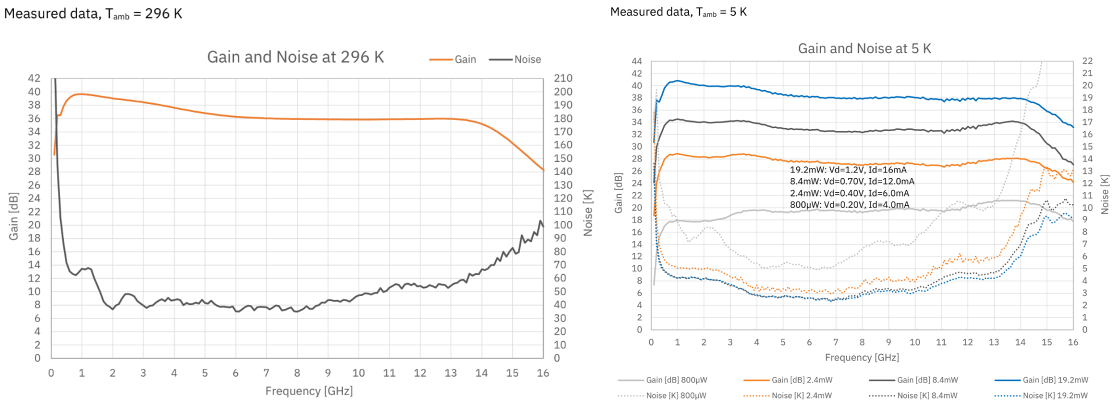


(a) Room Temperature ($T = 292.4\,\mathrm{K}$) (b) Low Temperature ($T = 4.35\,\mathrm{K}$)

Figure 5.8: Frequency versus gain amplifier tests at room and low temperatures

5.2.2 Analysis and Comparison to Expected Results

Figure 5.9 shows the expected amplification levels of our amplifier, as well as the noise levels of each temperature at those frequencies. They provide a figure of the gain (dB) and noise temperature (K) across a frequency range of 0 to 16 GHz, at temperatures of 296 K and at 5 K. At room temperature ($T = 296K$), the gain averaged at 37 dB, and the noise temperature produced by the amplifier is roughly 50K. At low Kelvin temperatures ($T = 5K$), the gain averaged at 40dB, and the noise temperature is significantly lower and averages around 4 K. Our results are comparable to the gain levels and the noise levels of the expected results, granted the limited frequency range. The expected results have slightly higher gain, though this could be due to how the tests we did were not at the ideal parameters of the amplifier outlined in Reference [9].



(a) Gain and Noise Graph at $T = 296$K

(b) Gain and Noise Graph at T=5K

Figure 5.9: Cryoamplifier Noise and Gain Graphs, Taken From Reference [9]

5.2.3 Ideal Parameters and Comparison of Previous System

Another test was done to identify the ideal parameters at low Kelvin temperatures, and Table 5 shows those parameters. If another test was done at both room and low Kelvin temperatures with these parameters, it is reasonable to assume that graphs such as Figure 5.9 would be produced.

Parameter	Value
Temperature (Kelvin)	4.62
Frequency (GHz)	1
V_{ds} (V)	1.2
I_{ds} (mA)	19.5
Gain (dB)	41.2

Table 5: Ideal Parameters

When comparing the cryogenic amplifier setup with our previous room temperature amplifier, we can note that the gain levels for both amplifiers are similar. The main difference here is the operating temperatures and the difference in the noise figures. For the cryogenic amplifier, there will be less noise to begin with since it is already at low Kelvin temperatures. It also has a noise figure as low as 0.05 dB, which makes for a very high signal to noise ratio [9]. While the room temperature amplifier also has a relatively low noise figure of 0.8 dB, the level of noise it is receiving to start with is higher (since it is at room temperature), and thus will have a lower signal to noise ratio than the cryogenic amplifier [13].

6 Conclusion

The results of this project show the successful implementation of the LNF-LNC0.3_14B, the cryogenic amplifier, into our cryostat. After careful soldering in accordance with data sheets, we were able to test the amplifier, our power supply, and power block, and we achieved reasonable results that show the effectiveness of the cryogenic amplifier. Following this, clearer signals can be received when conducting ESR experiments on various samples. Due to the fact that at low Kelvin temperatures, the noise temperature of electrical components is significantly lower, and the fact that the noise figure of our amplifier is around 0.08 dB, the old room temperature amplifier has become an unnecessary part of achieving the clear ESR signals.

Another important factor of this experiment was the design of the cryogenic amplifier holder, and deliberations about whether it had to be a heat load. The holder accounted for all essential pieces of the system, leaving space for wiring to be threaded, holding the amplifier snugly with screws, and providing a way to snap-on the holder in any baffle zone while being minimal enough to allow for other components such as the thermistor that was taped to it. After low Kelvin temperature tests, it was determined that this holder did not have to be a heat sink, as the convection of the partial gasses in the cryostat were enough to keep the cryochamber and the powered amplifier to temperatures well within the bounds of testing.

We have also confirmed the necessity of the switch as an important part of the Tube Apparatus. The next steps include further testing of the timing using the QICK with actual loop gap resonator to measure the ringdown. With careful consideration of the discrepancies involved in triggering the switch at room temperature, and eventual testing of the switch and the amplifier together, it is reasonable that the switch will be able to trigger at the correct times. Operable in low Kelvin temperatures, the switch will allow the pulses to pass through to the sample and elicit a response, and then it will be triggered at the right time, only allowing the response to be amplified by our cryogenic amplifier.

Finally, the experiments and results from this project allow for the use of the cryogenic amplifier in the cryostat. With further testing on the timing of the switch to be used, this apparatus will be ready to provide clearer ESR results than could be seen with the previous room temperature amplifier.

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