ETH Zürich

Semester Thesis

Ultra low noise amplifiers and their DC wiring

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April 7, 2010

Abstract

The research on superconducting qubits is a promising direction for the realization of a quantum computer. In order to be able to detect signals on a single photon level, tremendous amplifications at microwave frequency is needed. Here, the HEMT based Low Noise Amplifiers LNA197D and LNA209D from S. Weinreb of CalTech have been tested and equipped with appropriate wiring for power supply in order to use them for experiments inside the Oxford cryogen free Triton cryostat.

Contents

1 Introduction

At the Quantum Device Lab at ETH Zürich, Andreas Wallraff and his group perform experiments with superconducting qubits. A qubit or quantum bit is one unit of quantum information, just like a classical bit in electronics represents one unit of information. Unlike the classical bit, which is either in state 0 or in state 1, a qubit may also be in a state of superposition of 0 and 1. This leads to new possibilities like vast computing power or cryptography. These experiments are typically carried out in an ultra low temperature environment at temperature of about 20 mK in a dilution refrigerator. As a whole, they make up the Cryostat. In this semester thesis, DC wiring of the cryostat and the related components are discussed. Therefore two breakout boxes and the wiring for the power supply of the two amplifiers were manufactured and tested. The two boxes together provide control ports for twelve superconducting bias coils, four ultra low noise large bandwidth amplifiers and an RF switch.

2 HEMT- Low Noise Amplifier

As mentioned in the abstract, a typical signal power that has to be amplified is the signal power of a single photon that has a lifetime inside the cavity of the order of 1 μs. For these specific experiments, microwave photons are considered. The relation of frequency and energy is

$$E = h\nu \tag{1}$$

and for microwave photons of frequency $\nu \approx 6$ GHz this means an energy of about $4 \cdot 10^{-24}$ joule. With the typical lifetime for these photons a power of $4 \cdot 10^{-18}$ watt can be associated. This corresponds to -150 dBm, where a signal should be on the order of 0 dBm to make full use of the dynamic range of the digitizer card. Because of the low amplitude of these signals, the noise temperature of electrical devices (here the amplifiers) must be very low. Otherwise the signal vanishes within the background noise and may be detectable with a lot of averaging. Friis' formula

$$T_{tot} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 \cdot G_2} ... \tag{2}$$

states that for a cascade of amplifiers the total noise temperature T_{tot} [1] is dominated by the noise temperature T_1 of the first amplifier if the amplification factors G_n of each amplifier are sufficiently large. In case of the experiment, the +150 dBm are provided by 4 amplifiers of about +40dB each. So the first amplifier needs to have a very low noise Temperature. This condition together with a very large bandwidth is achieved using a HEMT (High Electron Mobility Transistor) amplifier that is capable of operating at frequencies greater than 10 GHz which is the domain of microwaves. The most basic idea is that HEMTs create a two dimensional electron gas by different doped semiconductors, see figure (1). This allows the transistor to quickly react on high frequency electric fields.

[1] In electronics, the noise temperature T is a temperature assigned to a component such that the noise power P delivered by the noisy component to a noiseless matched resistor is given by $P = B_n k_B T$, B_n the noise bandwidth [5]

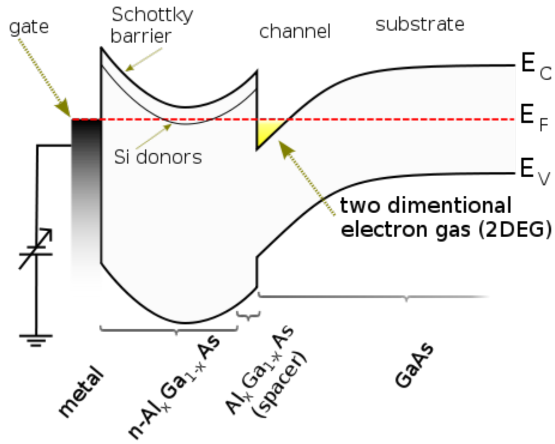


Figure 1: Two semiconductors with different fermi energies form a two dimensional electron gas. To further improve the electron mobility, the electrons of the highly doped left part migrate to the undoped GaAs where they have no impurities to collide with. [1]

3 Power Supply

The devices inside the cryostat, especially the amplifiers, need well defined voltages to perform according to their specifications. This requires special biasing equipment. Gabriel's bias box [2] provides a constant voltage supply which is crucial in order to achieve good results. Each voltage for drain and both gates can be adjusted individually with potentiometers to match the specifications of the amplifiers. For each channel the box provides three outputs:

1. One output at the rear is connected to the device.
2. One output on the front to measure the applied voltage.
3. Another output at the front to measure the current of the channel via a voltage [2].

This way the user has full control on the power output. This is necessary as the fridge has only limited cooling power. The bias box itself is powered by a commercial Agilent E3630A power supply providing ± 15 V

4 The Wiring

4.1 Heat load

Any device inside the cryostat that needs to be connected to a voltage source is a source of heat load. It takes some effort in order to have suited wiring as there are more demands than simply good connectivity. The major problem that is encountered with wiring is the fact that a high electrical conductivity usually comes along with a high thermal conductivity. A short wire has low resistance and will catch up less noise than a longer one, however, for a fixed temperature difference it carries more heat into the cooled parts of the cryostat. The exact (differential) relation is

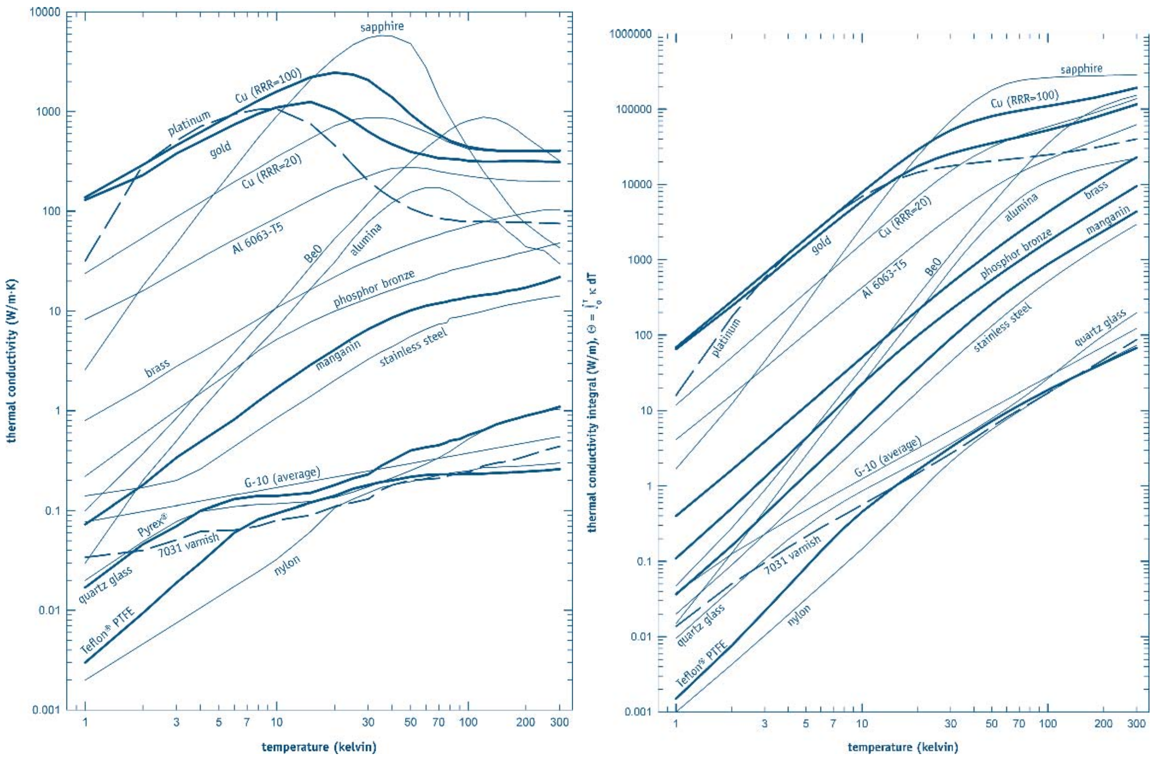


Figure 2: Temperature dependence of the thermal conductivity of various materials. Left: the absolute value. Right: the integral from T=0 °K to T=Θ. Taken from reference [3].

$$\dot{Q} = \frac{\lambda}{d} A \cdot \vec{\nabla} T(\vec{x},) \tag{3}$$

where $\dot{Q}$ refers to the heat flux through a cross section of a conductor, A to the size of the cross section, d to the length of the conductor and λ to the specific thermal conductivity of the material. T is the temperature at a place $\vec{x}$.

The balance point between signal quality and thermal input is primarily given by the cooling power of each thermal stage. In this case, the cooling is capable of carrying away about 1W at the 4 °K stage and 0.2 mW at the 0.1 °K stage. In order to calculate the total heat flux of a wire, one has to consider the temperature dependence of the thermal conductivity of a given material, as the wire is not isothermal. For a variety of materials, figure (2) shows the thermal conductivity as a function of temperature. To calculate the heat load, equation 3 has to be integrated. For easy computing, the integral has been calculated in advance and equation 3 simplifies to

$$\dot{Q} = \frac{A}{d} \cdot (\Theta_2 - \Theta_1), \tag{4}$$

where now $\dot{Q}$ is the total heat flux and Θ_1 and Θ_2 refer to the points of the thermal conductivity integral, see figure (2). Using this, one obtains a heat flow of about 1.5 mW if a wire of 24 copper braids of length 1 m and of 90 μm diameter connects the 300 °K and the 77 °K Kelvin stage. This is not significant, however, if the same wire connects the 77 °K

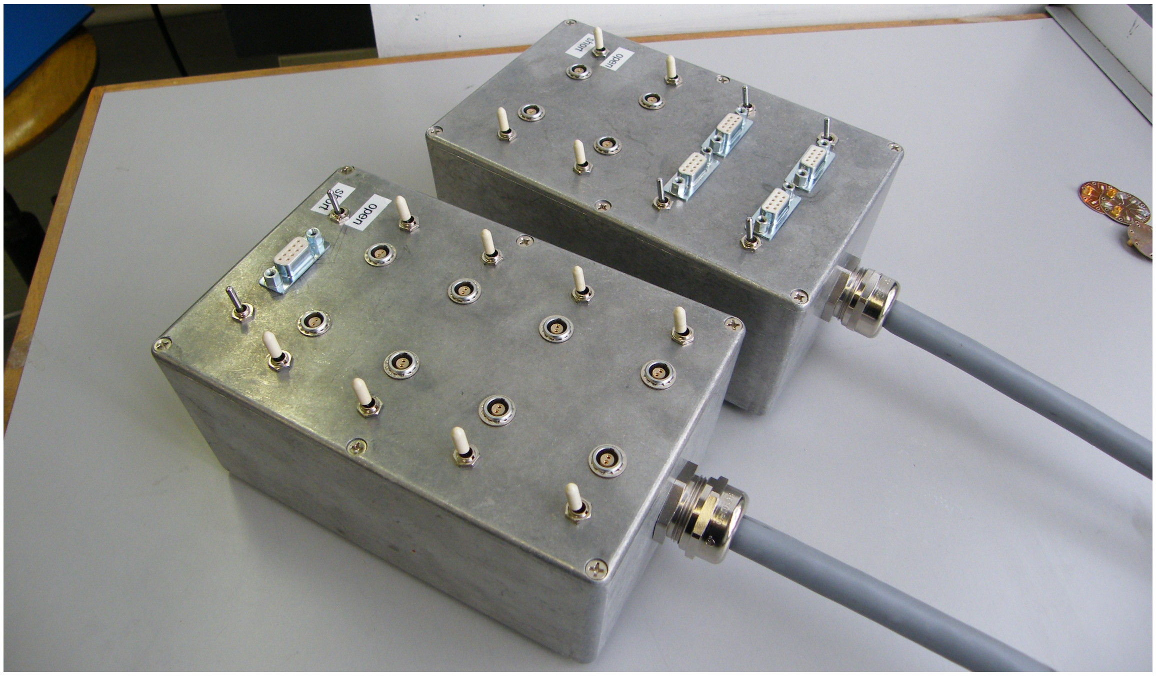


Figure 3: The two Breakout Boxes.

stage and the 4 °K stage, there is already an heat flux of 15 mW which is significant as the total cooling capacity of the 4 °K Stage is about 1 W.

4.2 Electrical Isolation and shielding

Another issue is the pickup of noise by the wire itself. This may be caused by thermal radiation or any electromagnetic field within the range of the wire. From this point of view, a short wire is preferred. If the wires are considered to have a current into the cryostat, Kirchhoff's law states that the same current flows out of the cryostat. By twisting any pair of wires the resulting electromagnetic field is minimized. This is why any pair of wires is twisted. In this case, any wire within the cryostat are twisted, and the main wire is a so called 'woven loom' which consists of 12 twisted pairs of braids embedded in a synthetic tissue.

A conducting shielding layer around any wire prevents further noise pickup in the sense of a Faraday cage. Wires at room temperature are shielded, however, inside the cryostat shieldings are omitted due to additional heat load.

4.3 The Breakout box

The wiring manufactured connects the bias box and the two LNAs. The first step is the breakout box, which can be seen in figure (3). Its purpose is the control over whether a channel is open for use or a short circuit to ground. Therefore, any channel has its own switch that connects the device either with its bias or with ground. Figure (4) shows the schematic circuit diagram for the switches used for the breakout box. For very sensitive applications it would be more suitable to additionally use potentiometers that have zero resistance while a channel is used. Before switching the channel to ground, the potentiometer would be used to apply a very high resistance that suppresses any electric pulse caused by the switch. However, this has not yet been implemented and may be difficult because of the spacial constrains within the box.

As mentioned in section 4.1, twisted wires were used preferably (see figure (14)). The big main wire of the breakup boxes is made up of twisted pairs by default. Each pairs is shielded separately and the whole main wire is also shielded. The wires inside the Box itself are twisted as good as possible considering the spacial constrains. For the connection to ground, resistors of 100 Ω serve as protection from high discharge currents. The main shielding of the main wire is grounded, that is connected to the plug on the front side which is connected to the cryostat. The shieldings of the individual pairs are also grounded. Furthermore, the breakout box renders it less difficult to keep track of each channel, resulting in a more ordered experimental setup. The documentation on pin assignment can be found in figure (12,13). In general the pin assignment uses the LEMO convention as one 24-pin LEMO vacuum feed through is used for each breakout box to connect room temperature to the cryogenic wiring, see [4].

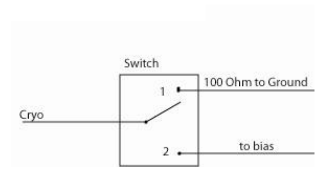


Figure 4: The schematic circuit diagram of the switches.

4.3.1 Manufacturing details

The breakout boxes are made of pressure casted aluminum. Figure (5) shows how the original box had to be modified. The round holes for the switches, LEMO plugs and screws were drilled in a common way, the trapezium like holes for the D-Sub 9 pin plugs were swaged. It had to be made sure that the distances between the plugs are sufficiently sized for the filters that will be attached to them. Another small hole on the front side was drilled for the grounding plug, and the big hole on the rear for the main wire was made under supervision of the ETH Lehrwerkstatt as it is too big for commonly available tools. The wires used inside the box are standard 0.4 mm diameter copper braid wires. Shrink-on tubing was attached only at nearly every second pin of the LEMO receptacle FGG.3B.324.CLAD12 due to the lack of space (see figure (15)). Inside the box, shrink-on tubing was rarely used as because the joints are less critical, the isolation of the wires better and the area was better accessible an therefore soldering was easier. The serrated lock washer of the two-pin LEMO plugs were used on the upper side of the box to transfer the torque as the LEMO plugs don't have a nut at which a tool could resist to the torque needed to fix the plug permanently.

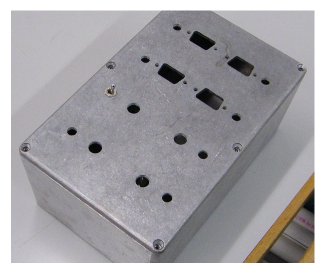


Figure 5: The first step is to drill/ swage the holes for the electrical components.

4.4 Wiring in the cryostat

A flange (see figure (16)) has been designed to carry two HGG.3B.324.CLLPV LEMO receptacle that connect the room temperature to the cryogenic wiring. From that LEMO

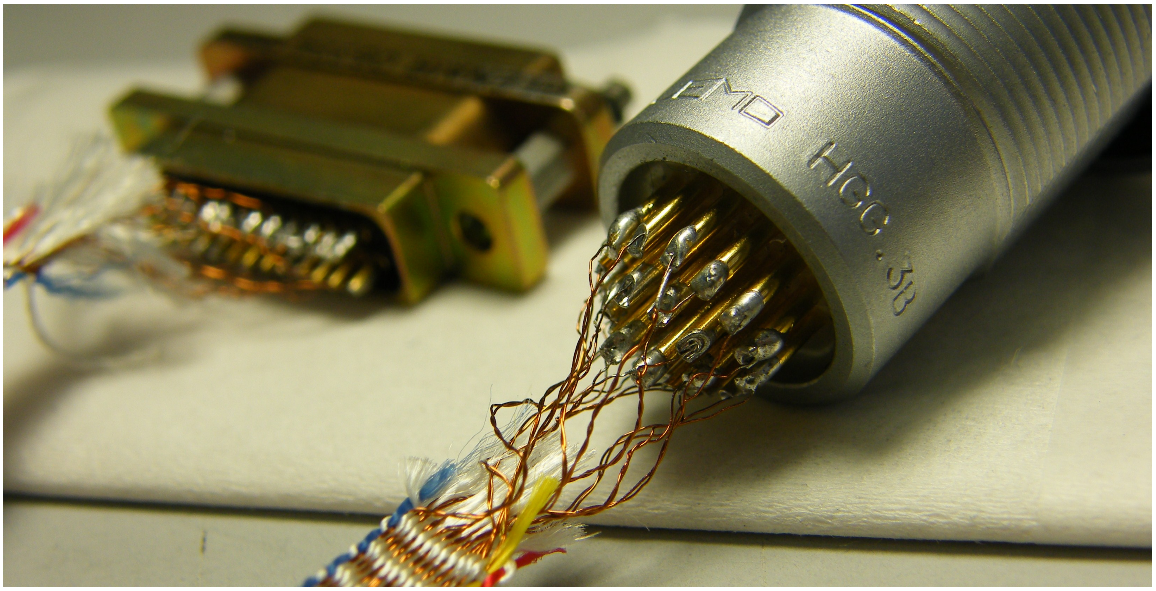


Figure 6: The soldering of the loom from the 24 pin LEMO plug to the micro D-Sub adapter. This part will be attached inside the cryostat.

adapter, about one meter of woven loom connects a micro D-Sub plug where the wires for the individual devices are attached. Because of their length, the heat load stays within an acceptable amount. The wire and its soldering is sensitive to mechanical stress, it is recommended to treat them carefully. The resistance of the wire measured from the input of the breakout box to the plug for the amplifiers is for each braid about 7 to 8 Ohms.

4.4.1 Manufacturing details

The soldering turned out to be rather difficult as the size of the sockets and the braids which are 90 μm in diameter are very small, and therefore hardly to be seen. It turned out to be practical if two persons solder the micro D-Sub adapter. Before soldering, the braids need to get removed their isolation. This can be done efficiently with a sharp blade. The wire may be fixed on a solid material such that the isolation can be skimmed off. This way one has full control on the length of the deisolated area which should not be more than two or three millimeters. For soldering, a piece of aluminum foil was put between the contacts such that the solder won't connect two contacts. One person holds the individual braid in the correct position and the second one actually solders it. Figure (7) shows the fixing of the plug for good handling. A flux on water basis and flux-free soldering tin was used. Early approaches of soldering with the help of a microscope failed. At the end, any channel was tested for conduction and short circuit.

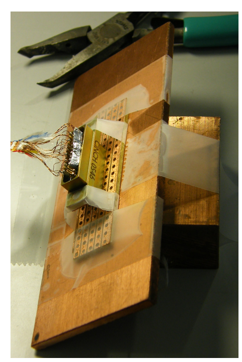


Figure 7: Soldering of the micro D-Sub plug.

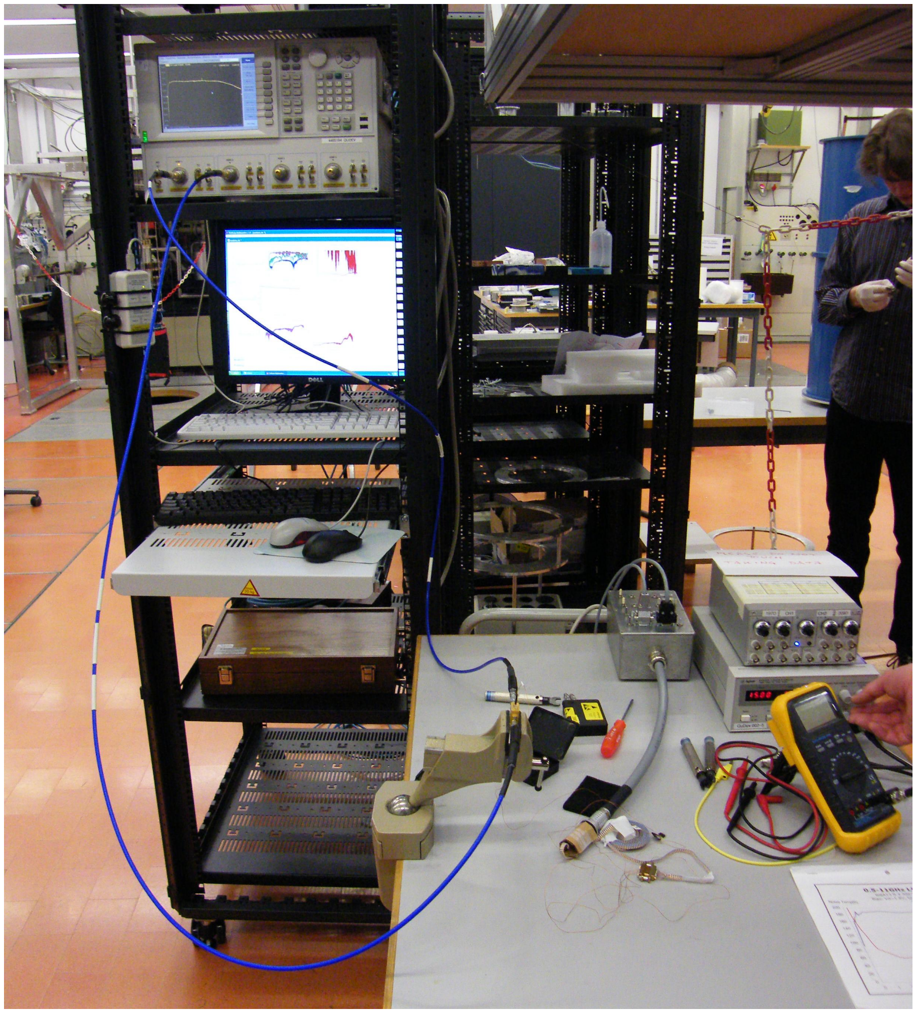


Figure 8: The setup. One can see the amplifier in the vice ant the blue microwave cables leading to the measurement device. On the right, there are the bias box, the breakout box, the voltage source and the multimeter witch the data provided in table [1] was taken with.

5 Measurement and characterization of the LNAs

5.1 Experimental setup

For the measurement of the LNAs, an Agilent E 3630E Network Analyzer was used to generate the signal and to measure the amplification. To avoid measuring at the region of saturation, the signal of -5dBm was damped by two -20 dB attenuators. Two wires were used, one for the input and one for the output of the LNA, each equipped with a DC block. After the calibration of the wires, the performance of the amplifiers could be directly measured. The parameters used are displayed in table (1). The measurement of figure (9) took place at room temperature.

		drain	gate 1	gate 2
LNA 197D	U	1.80 V	1.45 V	1.45 V
	U_I	74.5mV	1.08 V	1.08 V
	I	37.2 mA	0.1 mA	0.1 mA
LNA 209D	U	1.80 V	1.40 V	1.40 V
	U_I	69.5 mV	1.02 V	1.01 V
	I	35 mA	0.1 mA	0.1 mA
	k	0.5 $\frac{A}{V}$	0.1$\frac{mA}{V}$	0.1$\frac{mA}{V}$

Table 1: The parameters of the measurement. The voltages U/ U_I were set/ measured, the currents I calculated by I=k$\cdot U_I$, k a factor taken from p. 2 of [2]. The accuracy of the multimeter may be ± 1-2 mV.

5.2 Results

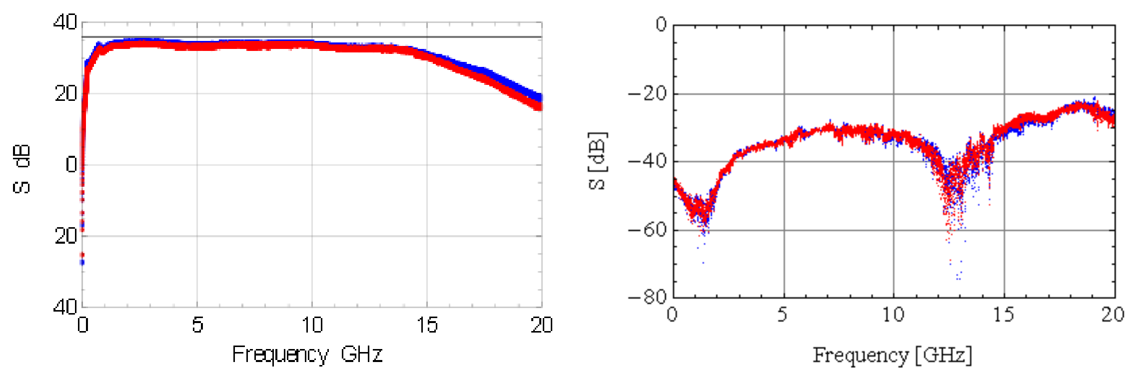


Figure 9: The data that was taken from LNA209D (red) and LNA197D (blue). Left: the amplification performance where the black line marks 36 db. Right: Reflections. Note: the axes have been shifted by +40dB to display the correct amplification.

The data taken can be seen in figure (9). Both amplifiers have nearly the same characteristics, actually they are intended to be equal. One sees the large bandwidth and low reflections.

5.3 Analysis

The most important thing is the large bandwidth with an almost constant amplification between 1 to 14 GHz. This property renders the amplifiers very valuable for the experiment.

Still, this data has to be compared to the specifications of the amplifiers. Figure (11) shows the specifications as provided by the manufacturer. The one difference to the data taken is the level of amplification, which is well above 36 dB. It turns out that there is a difference of about 2 to 5 dB. As figure (10) shows, this difference was there in a previous measurement from November 2008, though smaller by nearly 2 db. It has not yet been sorted out definitely where the difference comes from. Its a fact that the amplification

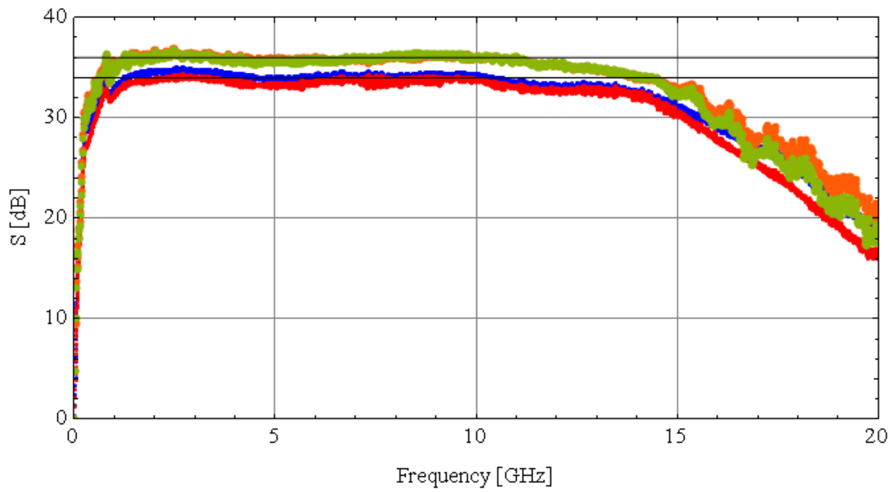


Figure 10: The two measurements in comparison. The two black lines mark 34 and 36 dB. Red and blue correspond to the new measurement, green and orange to the older one.

currents are a little lower than two years before. The difference in U_I of any channel is 6 to 7 mV which corresponds to a difference in each current I of 0.6 to 0.7 μA. However, the power difference associated is about 1.08 $\cdot 10^{-6}$ W. Another possible reason is the resistance of the wires, as the exact calibration of the older measurement is not known. At last, one of the amplification stages can be broken. This is however not very probably since any stage is expected to yield more than 2 dB. To be 100 percent sure, a quantitative noise temperature measurement needs to be performed.

6 Conclusion

Important parts of the wiring for the triton cryostat were manufactured and tested. This includes two breakout boxes for a total of 48 channels, one loom wire from 300 K to 4 K and two individual bias looms. The LNAs do have nearly the same performance as measured before, except a 2 dB difference. Though not big, it may prove significant to the experiment, since the noise temperature could potentially be degraded

7 Outlook

There has to be made a lot of wiring and installation of other devices before the experiments can start. Also, some improvements may be thought of; the discussion about the correct grounding resistance has not ended so far. Due to the lack of experimental data or experience, there can not be given a correct answer yet.

References

[1] http://en.wikipedia.org/wiki/High_Electron_Mobility_Transistor

[2] Gabriel Puebla: QuDev-001 Dual Channel Power Supply Q:\USERS\Gabriel\LaTeX\QuDev-001\QuDev-001.pdf

[3] www.lakeshore.com, Lake Shore Cryotronics, Inc.

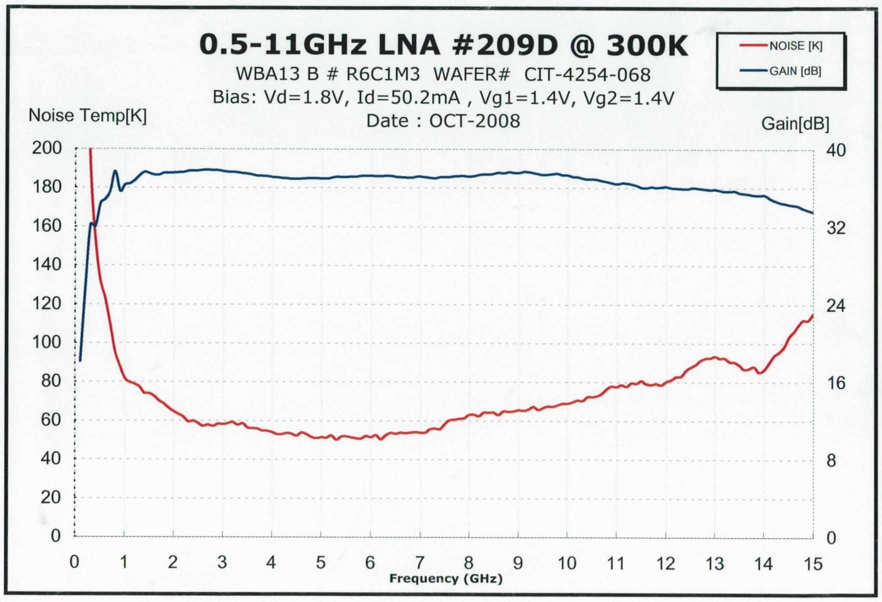
[4] http://intra.lemo.ch/catalog/ROW/UK_English/unipole_multipole.pdf page 50

[5] http://en.wikipedia.org/wiki/Noise_temperature

[6] Q:\USERS\Christian

[7] Q:\USERS\Christian \deckel

A Tables



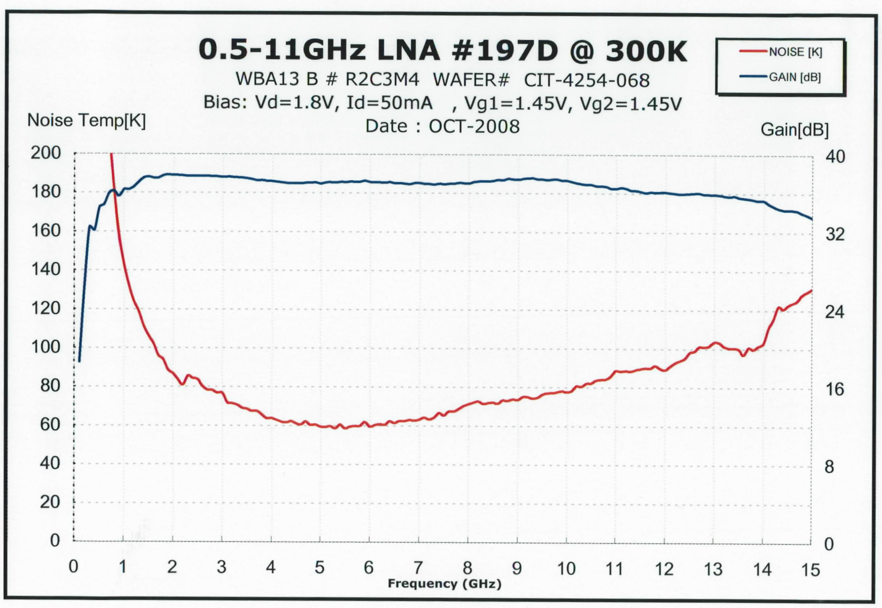


Figure 11: The specifications of both amplifiers.

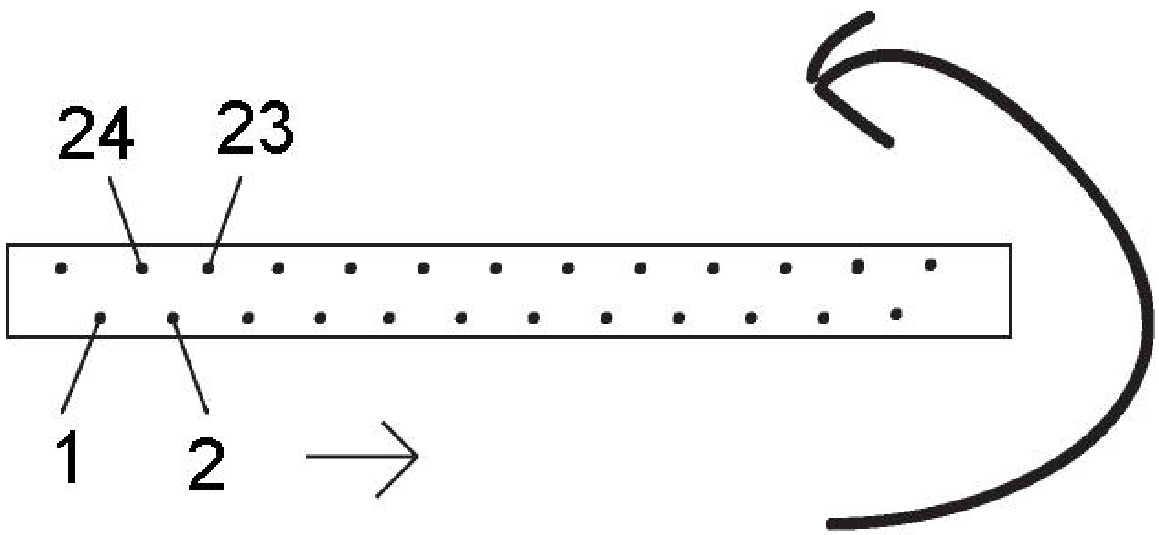


Figure 12: The pin assignment of the micro D-Sub plug. Pins 1 to 8 were used for the two amplifiers.

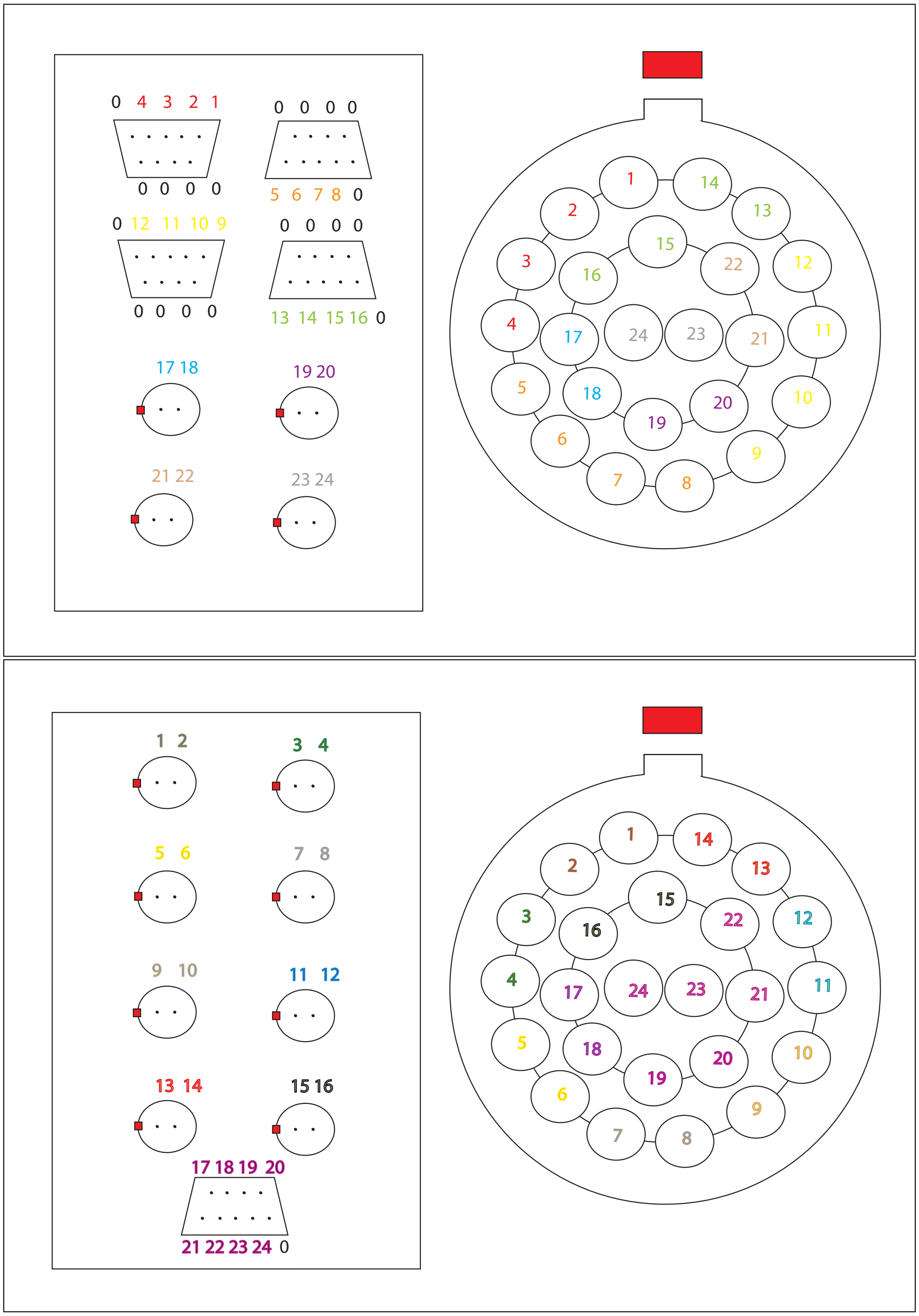


Figure 13: The Pin assignment for both breakout Boxes: top view for the box an the corresponding female LEMO plug attached to the cryostat. Box 1 (top) is made for up to four amplifiers and four 2 port devices like superconducting coils. Box 2 (bottom) is made for 1 RF switch with eight pins and up to 8 2 port devices. The files are available at [6].

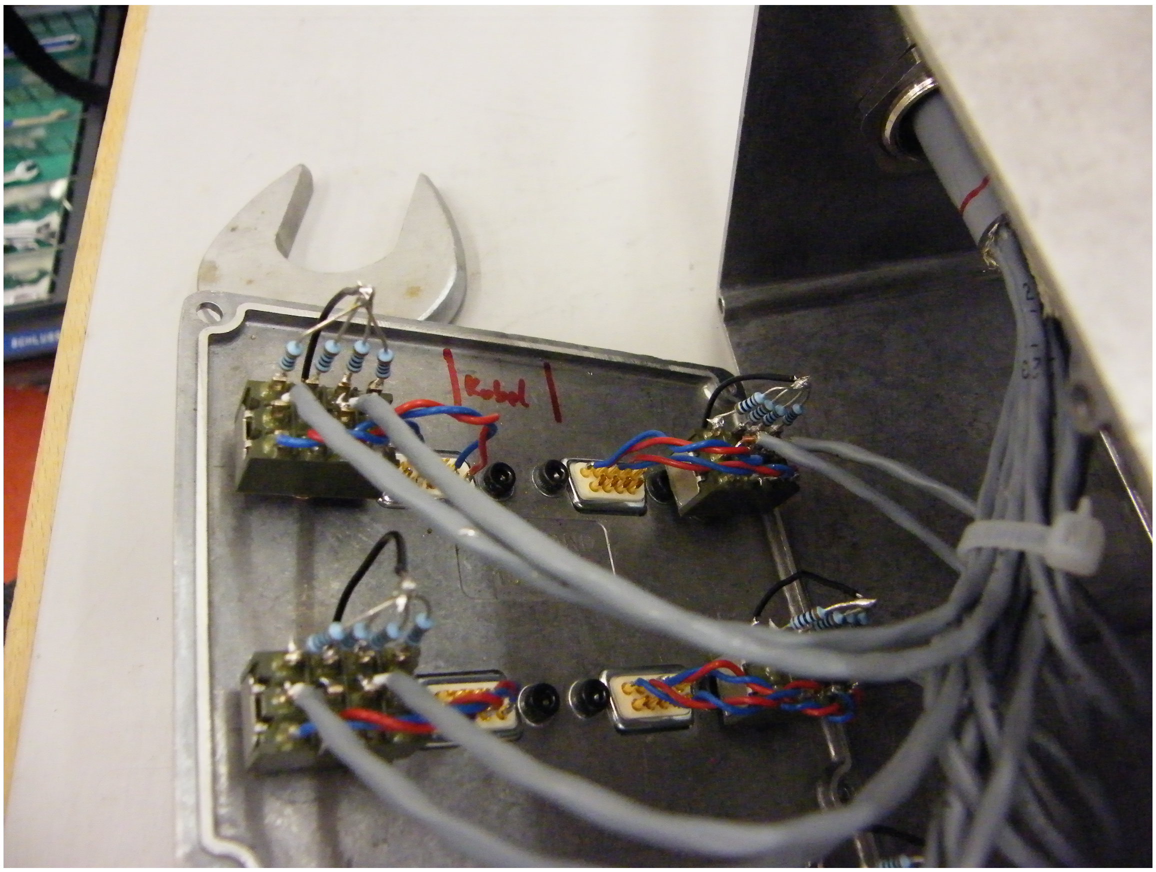


Figure 14: The inside of a breakout box from before the individual grounding had been added. one can see the twisted wires, the 100 Ω resistors, the main wire and its components and the LEMO plugs and switches. Notice the red mark that shows how far the wire is shifted from default position.

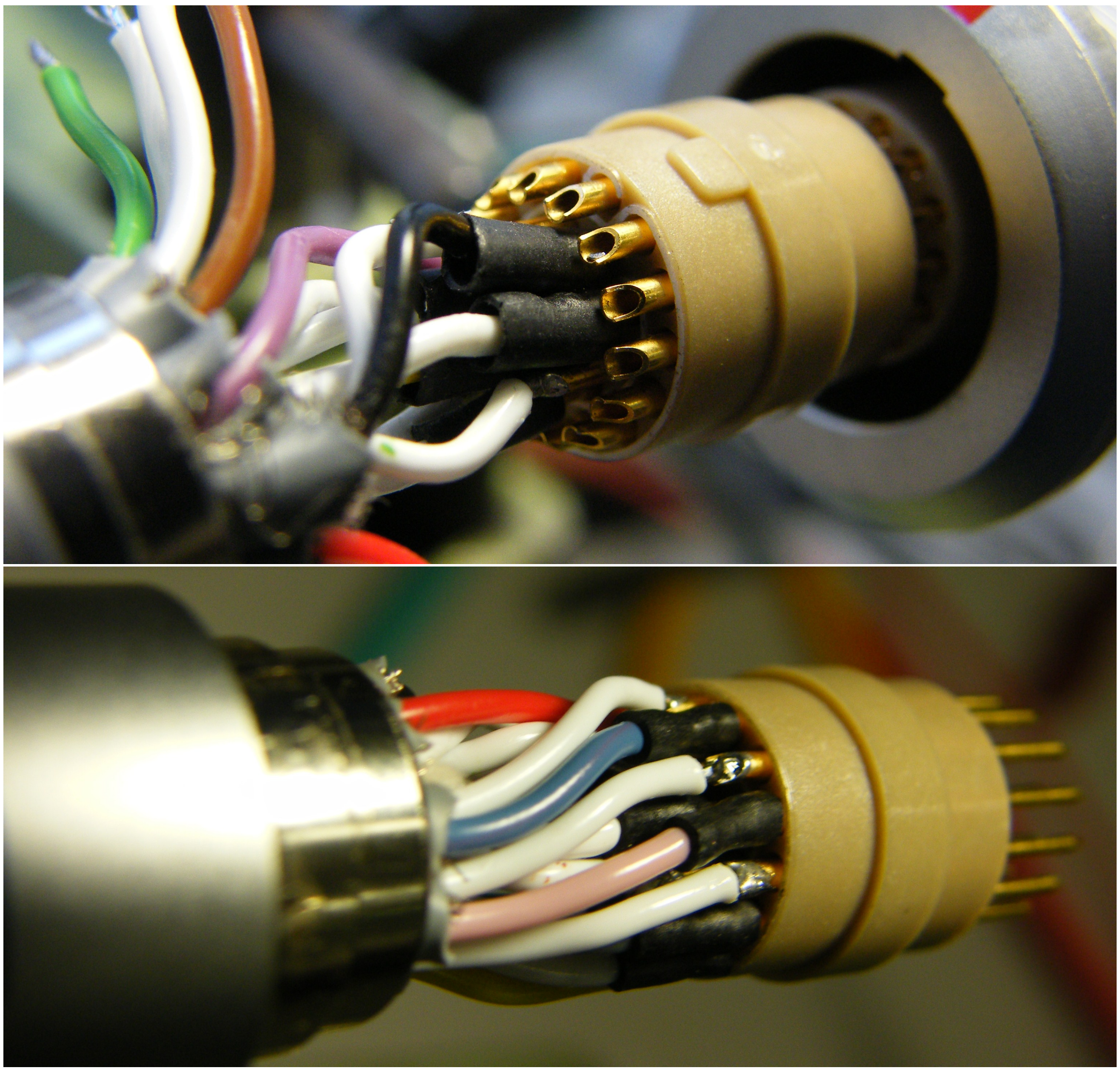


Figure 15: Two stages of soldering the 24 pin LEMO plug onto the breakout box's main wire. One can see the shrink-on tubing on some pins to avoid short circuits.

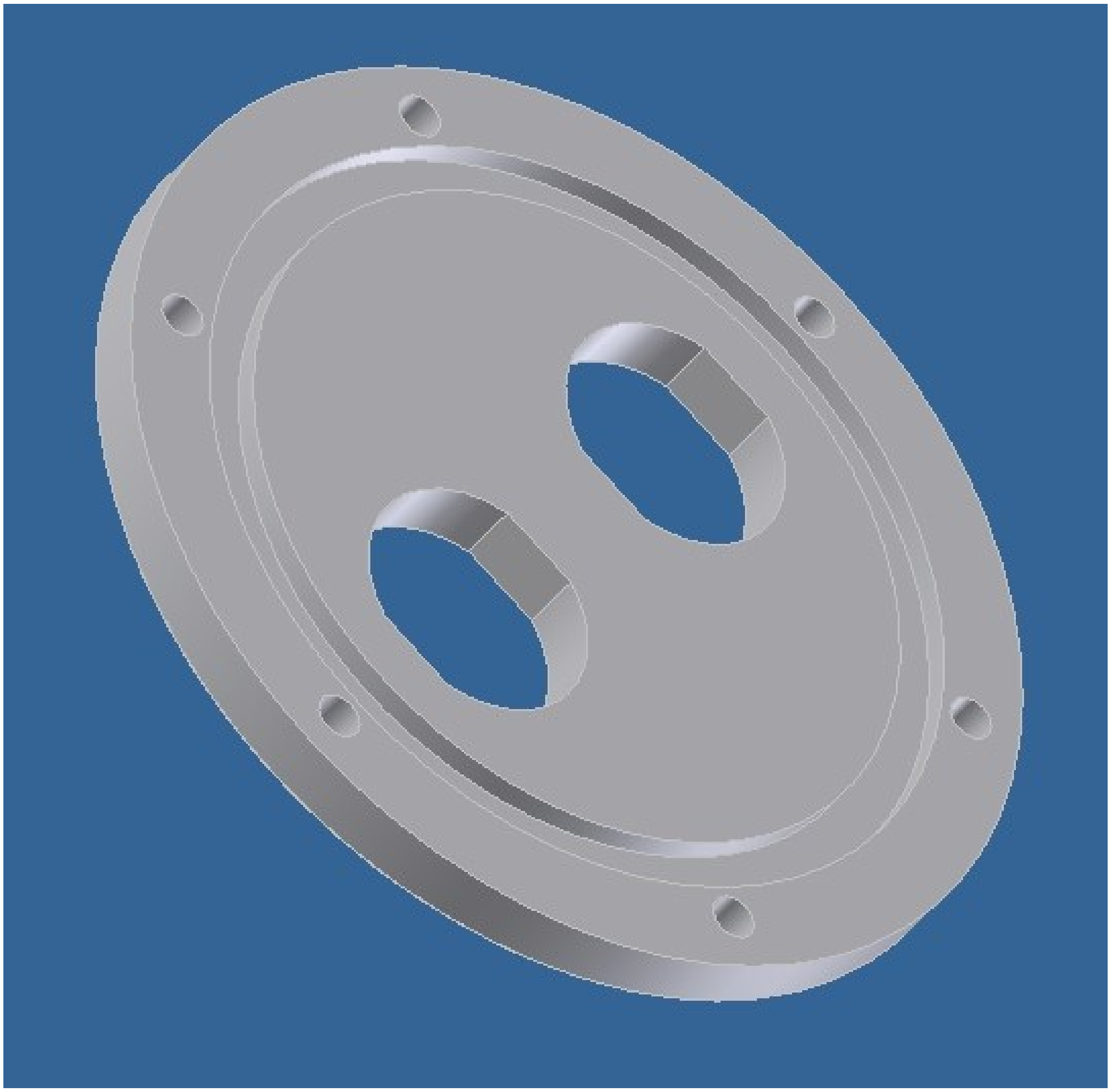


Figure 16: The flange that connects the interieur of the cryostat to the outside. Files available at [7]

Mathematica Appendix

LNA measurements

Old measurement

In[9]:=
```
SetDirectory[NotebookDirectory[]];
filenames = FileNames["*.txt"];
S21files =
 Select[filenames, And[! StringMatchQ[#, "test*"], ! StringMatchQ[#, "base123*"]] &]
{"LNA-197D.txt", "LNA-209D.txt"}
 MyInset = Framed[Grid[
   Table[{Style[StringReplace[ S21files[[i]], ".txt" → ""], ColorData[1, "ColorList"][[
        Mod[i, 15, 1]]]], 15]}, {i, 1, S21files // Length}], Alignment → Left]]
datasets = Table[{#[[1]] / 10^9, #[[2]]} & /@ Import[S21files[[i]], "TSV"],
   {i, 1, S21files // Length}];
S21files
dataplots = Table[ListPlot[# - {0, (i - 1) * 0} & /@ datasets[[i]], Frame → True,
   PlotStyle → {ColorData[1, "ColorList"][[Mod[i, 15, 1]]], PointSize[0.01]},
   LabelStyle → {FontFamily → "Helvetica", FontSize → 16}, ImageSize → 400, Axes → False,
   FrameLabel → {"Frequency [GHz]", "Attenuation [dB]", ToString[S21files[[i]]]}],
  {i, 1, datasets // Length}]
Grid[{{Show[dataplots, Epilog → Inset[MyInset, Scaled[{1.1, 0.5}], {Left, Center}],
    FrameLabel → {"Frequency [GHz]", "Attenuation [dB]"}], MyInset}}]
lnaalt = Show[dataplots];
```

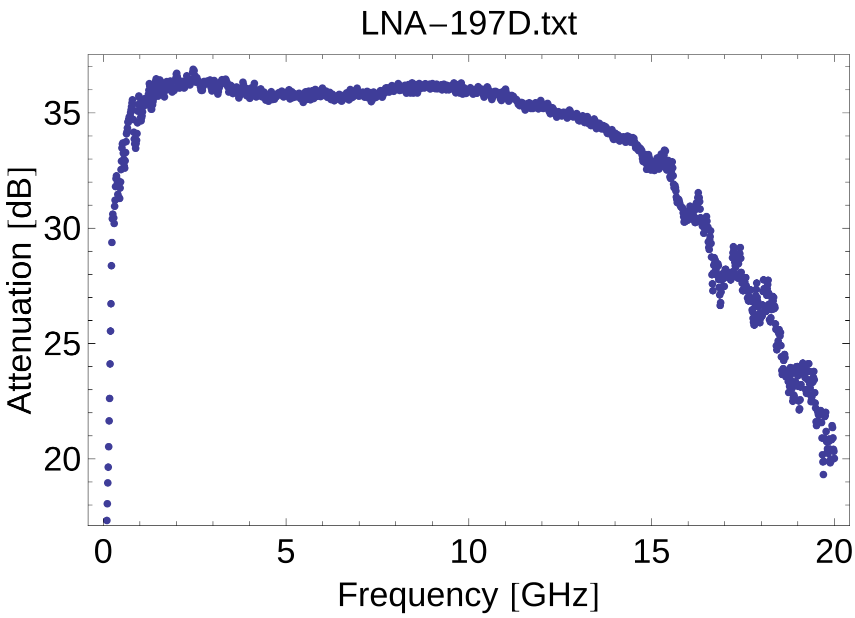
Out[11]= {LNA-197D.txt, LNA-209D.txt}

Out[12]= {LNA-197D.txt, LNA-209D.txt}

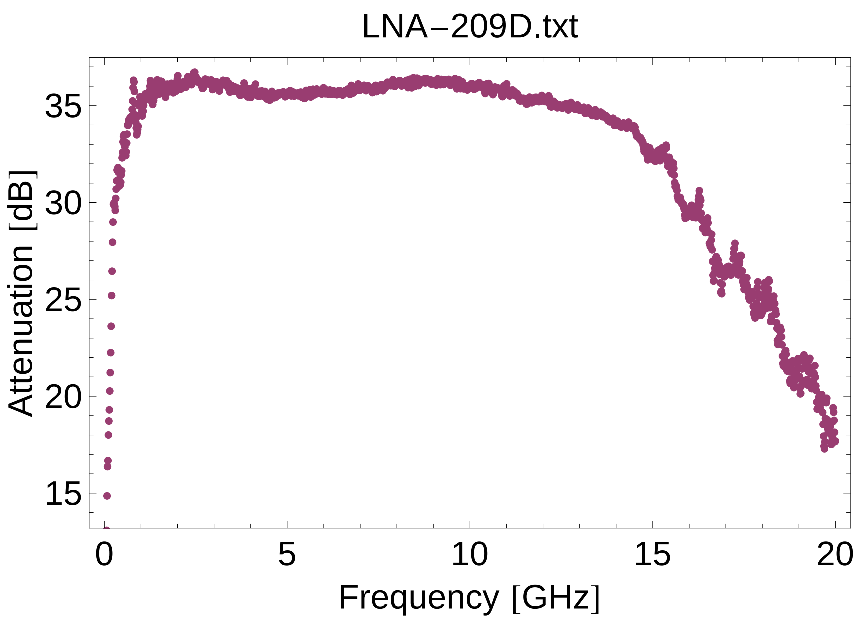
Out[13]=
LNA-197D
LNA-209D

Out[15]= {LNA-197D.txt, LNA-209D.txt}

Out[16]= {

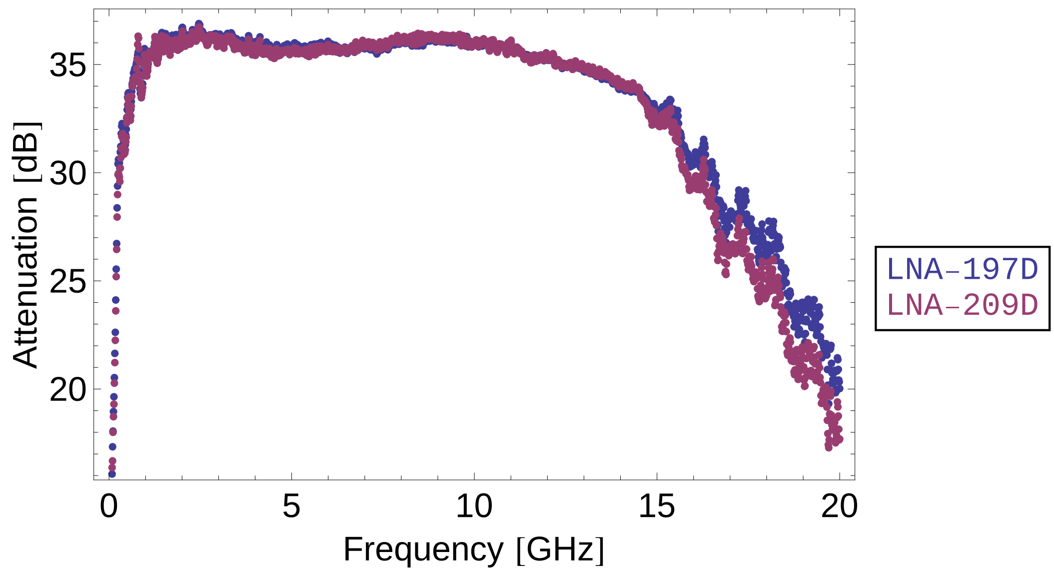

LNA−197D.txt
Attenuation [dB]
Frequency [GHz]
35
30
25
20
0
5
10
15
20

,


LNA−209D.txt
Attenuation [dB]
Frequency [GHz]
35
30
25
20
15
0
5
10
15
20

}

Out[17]=



New measurement

In[19]:=

```
(* Returns {frequencies,S11dB,S11ϕ,S12dB,S12ϕ,S21dB,S21ϕ,S22dB,S22ϕ} *)
Loads2p[filename_] := Transpose[Drop[Import[filename, "Table"], 9]]
SetDirectory[NotebookDirectory[]];
Splotparams = {Frame → True, FrameStyle → Directive["Arial", 14],
   FrameLabel → {"Frequency  [GHz]", "S [dB]", "", ""}, ImageSize → 350,
   GridLines → Automatic, PlotRange → {{0, 20}, {-80, 0}}, Axes → False};
Slistplotparams = {Frame → True, FrameStyle → Directive["Arial", 14],
   Joined → True, PlotStyle → {Red, Darker[Red], Blue, Darker[Blue]},
   FrameLabel → {"Frequency  [GHz]", "S [dB]", "", ""}, ImageSize → 350,
   GridLines → Automatic, PlotRange → {{0, 20}, {-60, 0}}};
VSWRplotparams = {Frame → True, FrameStyle → Directive["Arial", 14],
   FrameLabel → {"Frequency  [GHz]", "VSWR", "", ""}, ImageSize → 350,
   GridLines → Automatic, PlotRange → {{0, 20}, {1, 2.0}}, Axes → False};
VSWRlistplotparams = {Frame → True, FrameStyle → Directive["Arial", 14], Joined → True,
   PlotStyle → {Red, Darker[Red]}, FrameLabel → {"Frequency  [GHz]", "VSWR", "", ""},
   ImageSize → 350, GridLines → Automatic, PlotRange → {{0, 20}, {1, 2.0}}};
VSWRThresholdPlot = Show[Plot[{1.08}, {x, 0, 18}, PlotStyle → {Green}],
   Plot[{1.1}, {x, 0, 23}, PlotStyle → {Darker[Green, 0.8]}]];
```

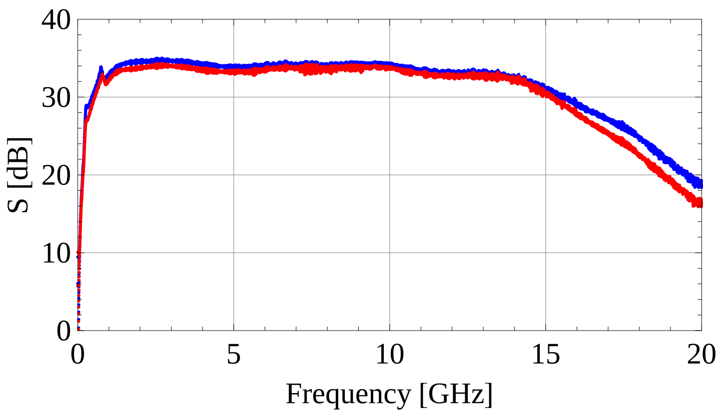
$$\texttt{S11toVSWR[data\_]} := \left\{\#[[1]],\ -\left(\frac{1 + 10^{-\#[[2]]/20}}{1 - 10^{-\#[[2]]/20}}\right)\right\}\ \&\ /@\ \texttt{data}$$

amp tests

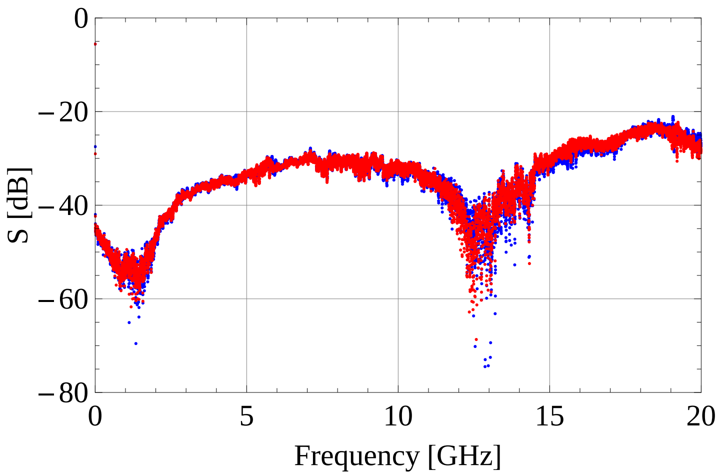
In[72]:=
```
fileList = FileNames["*.s2p"]
(*fileList=Select[fileList,
  StringMatchQ[#,"*neu2*"]||StringMatchQ[#,"*neu3*"]||StringMatchQ[#,"*neu*-1*"]&]*)
(*fileList=Select[fileList,StringMatchQ[#,"*cable*"]&]*)
dataTables = Loads2p[#] & /@ fileList;
S11vsf = Transpose[{#[[1]] / 10^9, #[[2]]}] & /@ dataTables;
S12vsf = Transpose[{#[[1]] / 10^9, #[[4]] + 40}] & /@ dataTables;

Splot = ListPlot[#, Join[Splotparams]] & /@ ({S11vsf, S12vsf}^T);
vswr1 = S11toVSWR[#] & /@ S11vsf;

VSWRplot = Show[ListPlot[#, VSWRlistplotparams], VSWRThresholdPlot] & /@ ({vswr1}^T);
plotTable = Row[#] & /@ ({fileList, Splot, VSWRplot}^T);
lnaneu = ListPlot[{S12vsf[[1]], S12vsf[[2]]},
  {Frame → True, FrameStyle → Directive["Arial", 14],
   FrameLabel → {"Frequency [GHz]", "S [dB]", "", ""}, ImageSize → 350,
   GridLines → Automatic, PlotRange → {{0, 20}, {0, 40}}, Axes → False},
  PlotStyle → {{Blue, PointSize[0.005]}, Red, Black,}, AspectRatio → 0.5]
noisenew = ListPlot[{S11vsf[[1]], S11vsf[[2]]},
  {Frame → True, FrameStyle → Directive["Arial", 14],
   FrameLabel → {"Frequency [GHz]", "S [dB]", "", ""}, ImageSize → 350,
   GridLines → Automatic, PlotRange → {{0, 20}, {-80, 0}}, Axes → False},
  PlotStyle → {{Blue, PointSize[0.005]}, Red, Black}, PlotStyle → PointSize[.0005]]
a = Plot[{36, 34}, {x, 0, 20}, PlotStyle → Black];
```

Out[72]=
```
{197D 300K s21 s11-40dB.s2p, 209D 300K s21 s11-40dB.s2p,
 cablesUncalib.s2p, calibratedThrough.s2p}
```

Out[80]=



Out[81]=

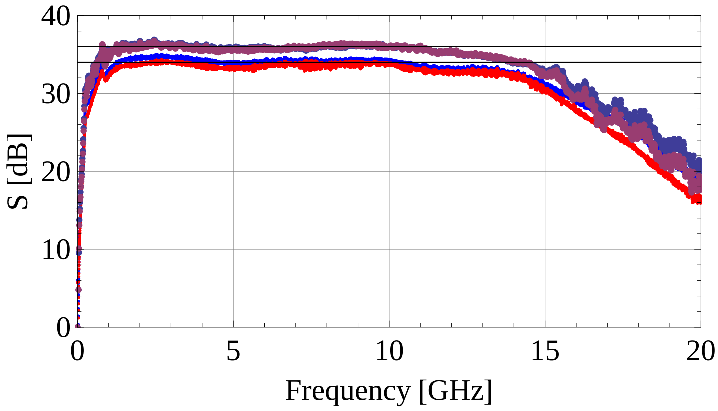


Combination

In[83]:=

```
Show[lnaneu, lnaalt, a]
```

Out[83]=



Heat load

In[84]:=

```
l = 1 ; (*lenth*)
A = π * (0.00009 / 2) ^2; (* 0.000009=90micrometer, the diameter, so A=cross section*)
n = 24; (*number of braids*)
theta2  =  110 000; (*see graphic*)
theta1 = 100 000;
deltaT1 = 300 - 77; (*not used in calculation, is related to theta*)

Q1 = n * A/l * (theta2 - theta1)  (*in watts*)

theta3 = 100 000;
theta4 = 1000;
deltaT2 = 77 - 4;
Q2 = n * A/l * (theta3 - theta4) (*in watts*)
```

Out[87]= 0.00152681 Null

Out[91]= 0.0151155