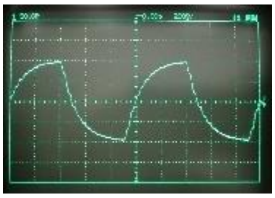
High impedance low-temperature readout electronics with a *RLC* tank: simulation and experimental results

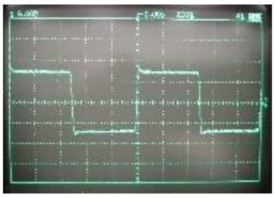
Consider, under cryogenic conditions, a 1 MHz source signal e_s with an impedance of R_s = 10 kΩ, that is connected via a 1 meter long 50 Ω coaxial-cable (coax) to a room temperature amplifier (RT amp). 1 meter 50 Ω coax corresponds to a capacitance C_{cab} = 100 pF.

First, we examined the capacitance effect of a 1 meter 50 Ω coax by connecting its one end to a 1 MHz square wave voltage generator with an impedance of around 200 Ω:

- if the impedance of the other end is not a 50 Ω resistor, the typical input impedance of a RT amp, but much higher, e.g., 1 MΩ, the capacitance effect of the coax can be found as shown on the right;

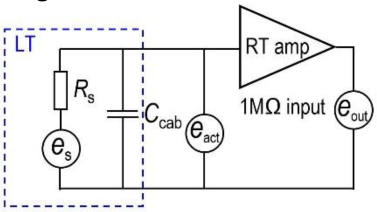


- if the other end is connected to a 50 Ω resistor, the typical input impedance of a RT amp, almost no distortion is found as shown on the right.



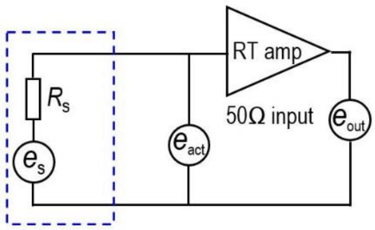
This result is in agreement with the paper https://doi.org/10.1126/science.280.5367.1238, i.e., "If the characteristic impedance of the coaxial cable, Z_0, is equal to the amplifier's input impedance, then the effective impedance of the cable plus amplifier is purely real and equal to Z_0."

By using an 1 MΩ input RT amp, e.g., NF SA-220F5, the capacitance of the coax must be included in the electronic diagram as shown below



The actual voltage at the 1 MΩ input RT amp can be calculated at 1 MHz, giving $e_{act} \approx 0.15e_s$ or $e_{act}/e_s \approx$ -16dB; the source signal is greatly decreased! It should be mentioned that to simplify the calculation, the input capacitance of the RT amp is not taken into account and if it is included, the signal loss will be even greater.

By using a 50 Ω input RT amp, e.g., NF SA-230F5, the coax can be omitted in the electronic diagram as shown below



The actual voltage at the input of the 50 Ω input RT amp is $e_{act} \approx (50/10000)e_s = 0.005e_s$ or $e_{act}/e_s \approx$ -46dB; indeed, the source signal is almost totally lost!

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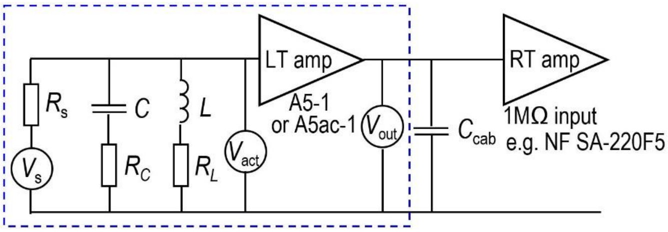
To avoid loss of high impedance signals under cryogenic conditions, the used method for the readout is to introduce an appropriate *RLC* tank and a low temperature (LT) amp.

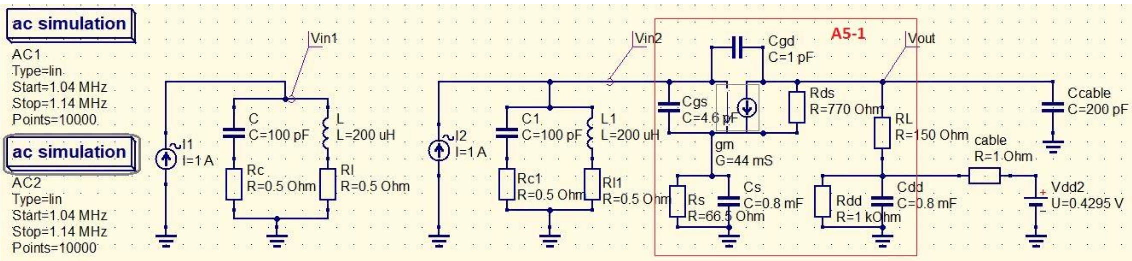
1. Readout chain 1: *RLC* + A5-1 + 2 meter coax + 1 MΩ input RT-amp

If the RT amp is with a 1 MΩ input (e.g., NF SA-220F5), "readout chain 1" includes a *RLC* tank, the LT-amp A5-1 or A5ac-1 (https://cryohemt.com/index.php/products/), and a capacitance of the coax C_{cab}, as shown below.

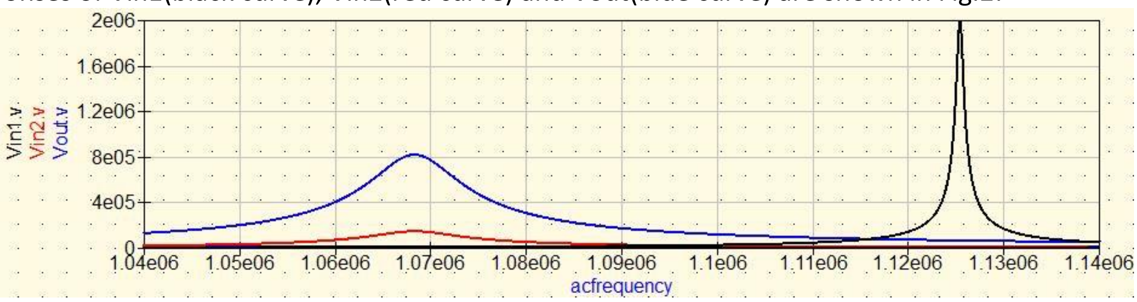


***The RLC* resonator** has an inductance L = 200 µH, a capacitance C = 100 pF, and series resistances $R_C = R_L$ = 0.5 Ω. Intrinsic values of the *RLC* are: the resonant frequency f_0 = 1.12 MHz, the quality factor $Q_0 = 1.41\times10^3$, the resonant impedance Z_0 = 2.00 MΩ.
LT-amp A5-1 characteristics: voltage gain A_{Vo} = 5.5 (with R_L = 150 Ω in Fig.1), input impedance is 10 pF // 10^{13} Ω, output impedance is 130 Ω, bandwidth with an input impedance of 50 Ω (and an output with 2 meter coax) is DC – 6.1 MHz.

The simulation circuit is shown in Fig.1 and the simulation is done using the free software Qucs (Quite universal circuit simulator). For the simulation, the source signal voltage V_s and its impedance R_s are replaced by current stimulus, I_1 for the *RLC* tank alone and I_2 for the "readout chain 1", respectively. This allows us to compare impedance values at resonant frequencies. To facilitate estimations, values of 1 A are used for current stimulus: Vin1 (resonator alone) is the intrinsic *RLC* voltage, Vin2 is the actual *RLC* voltage in the "readout chain 1", Vout is the output voltage of the LT-amp A5-1. The capacitance of a 2 meter coax is set C_{cab}= 200 pF. To simplify the simulation, the resistance and capacitance of the RT-amp input are not taken into account.

Fig.1


Frequency responses of Vin1(black curve), Vin2(red curve) and Vout(blue curve) are shown in Fig.2.

Fig.2


From the data in Fig.2:

- f_0 is shifted to f_2 = 1.07 MHz which is due to the input capacitance and the Miller effect of A5-1.

- The actual impedance Z_2 at the resonant frequency f_2, deduced from Vin2, is 151 kΩ while the intrinsic impedance Z_o at the resonant frequency f_o, deduced from Vin1, is 2.00 MΩ. The actual value Z_2 is much lower than the intrinsic one Z_o,

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which is due to the feedback of coax capacitance via A5-1. This shows also that the "readout chain 1" configuration suffers the feedback from output to input.

- From fig.2, Vout = 824 kV and Vin2= 151 kV, one can deduce that the voltage gain Vout/Vin2 is 5.5 ≈ A_{V0}. Using the input impedance Z_2 = 151 kΩ (with R_S = R_L = 0.5 Ω), the voltage gain A_V of the "readout chain 1" at 1 MHz as a function of the signal impedance R_s can be calculated and is shown in Fig.3. Indeed, with the increase of the 1 MHz source signal impedance R_s, the actual voltage gain A_V of the "readout chain 1" at 1 MHz decreases, e.g., with R_s ≈ 70 kΩ, $A_V \approx A_{V0}/\surd 2$.

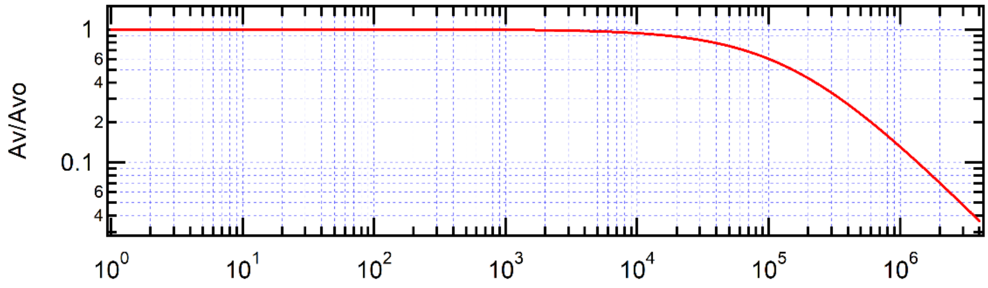


Fig.3

- the actual quality factor of *RLC* in the "readout chain 1" deduced from data of Vin2, Q_2 = 112 is drastically decreased compared to the intrinsic one $Q_0 = 1.41\times10^3$, or only 7.9% of Q_0. Again, this is due to the feedback of C_{cab} via A5-1. In addition, it is verified that in "readout chain 1", the quality factor at its output Q_{out} is the same as that at its input Q_2, i.e., $Q_{out} = Q_2$.

By using the same circuit as in Fig.1 and varying series resistances from $R_L = R_C$ = 0.5, 1.5, 3.0 to 5.0 Ω, simulated data are listed in Tab.1:

R_L=R_C (Ω)	Vin1 (kV)	Vin2 (kV)	Vout (kV)	f_0 (MHz)	f_2 (MHz)	Q_0	Q_2	Q_2/Q_0	Z_0 (kΩ)	Z_2 (kΩ)	Z_2/Z_0
0.5	2000	151	824	1.125	1.068	1.41×10^3	112	0.079	2000	151	0.076
1.5	667	131	715	1.125	1.068	471	98	0.21	667	131	0.19
3.0	333	110	597	1.125	1.068	236	81	0.34	333	110	0.33
5.0	200	89.8	489	1.125	1.068	141	66.5	0.47	200	89.8	0.45

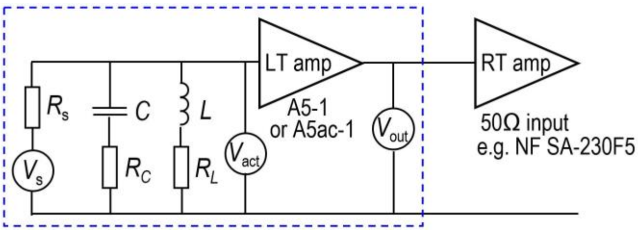
Tab.1

With the increase of R_L=R_C:
- the intrinsic Q_0 and the actual Q_2 decrease; the increase of Q_2/Q_0 is the result of the decrease of feedback effect.
- the intrinsic Z_0 and the actual Z_2 decrease; similarly, the increase of Z_2/Z_0 is also due to the decrease of the feedback effect.
- the voltage gain of V_{out}/V_{in2} ≈ 5.5 is constant; however, the input impedance Z_2 decreases.

With the increase of series resistance, the feedback effect will decrease. On the other hand, the input impedance of "readout chain 1" will decrease.

2. Readout chain 2: *RLC* + A5-1 + 2 meter coax + 50Ω input RT-amp

If the RT amp is with 50 Ω input (e.g., NF SA-230F5, or Femto HSA-X-1-40), the capacitance of the coax can be omitted and the "readout chain 2" is as below



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***RLC* resonator with an inductance L = 200 µH, a capacitance C = 100 pF, and series resistances $R_C = R_L$ = 0.5 Ω**

Intrinsic values of the *RLC* are: f_0 = 1.12 MHz, $Q_0 = 1.41\times10^3$, Z_0 = 2 MΩ

The LT-amp A5-1 characteristics input impedance is 6.5 pF // 10^{13} Ω, output impedance is 130 Ω in parallel with 50 Ω of the input impedance of RT amp, the voltage gain A_{V0} is reduced to A_{V0} = 1.56, and the bandwidth with an input impedance of 50 Ω is DC – 390 MHz.

The simulation circuit is as in Fig.4: the output of the LT-amp @≤4.2K is 130 Ω which is connected to 50 Ω of the input of the RT amp SA-230F5.

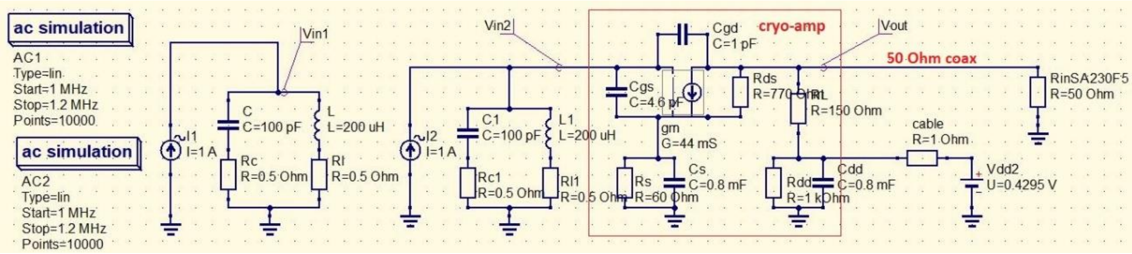

Fig.4

The frequency responses of Vin1, Vin2 and Vout are shown in Fig.5: Vin1 (resonator alone) is the intrinsic *RLC* voltage, Vin2 is the actual *RLC* voltage in the "readout chain 2", Vout is the output voltage of A5-1.

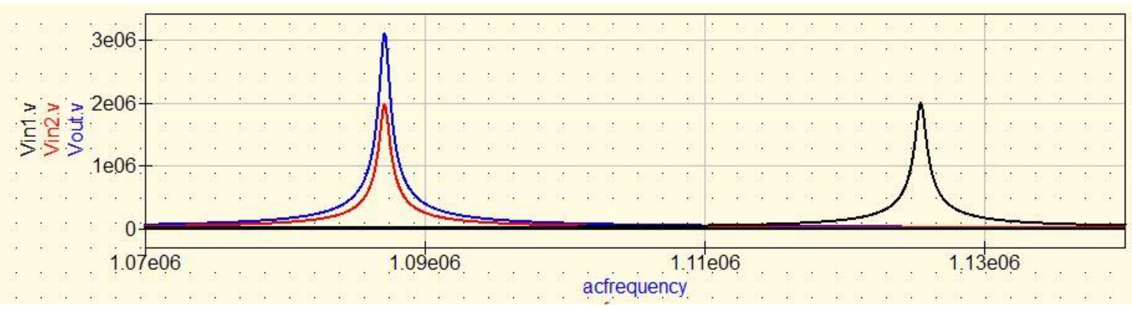

Fig.5

Deduced data are listed in Tab.2:

Tab.2

R_L=R_C (Ω)	Vin1 (kV)	Vin2 (kV)	Vout (kV)	f_0 (MHz)	f_2 (MHz)	Q_0	Q_2	Q_2/Q_0	Z_0 (kΩ)	Z_2 (kΩ)	Z_2/Z_0	Vout/Vin1
0.5	2000	1980	3114	1.125	1.087	1.41×10^3	1.45×10^3	1.03	2000	1980	0.99	1.56

Indeed, results in Tab.2 show that the input impedance and the quality factor of the "readout chain 2" are very close to the intrinsic values of the *RLC* (with $R_S = R_L$ = 0.5 Ω) and variations are only 1% for Z and 3% for Q. This implies that the feedback effect from output to input in "readout chain 2" is much smaller than that in "readout chain 1".

One question raised is which is the maximum attainable input impedance Z_2 of the "readout chain 2" for which the feedback effect is still relatively small. By varying R_L=R_C from 1 Ω to 1 mΩ in the circuit as shown in Fig.4, Z_2 values are reported in Tab.3:

Tab.3

R_L=R_C (mΩ)	1000	500	100	50	10	5	1
Z_2 (MΩ)	0.994	1.98	9.60	18.5	71.5	111	201
Z_0 (MΩ)	1.00	2.00	10.0	20.0	100	200	1000
Z_2/Z_0	0.99	0.99	0.96	0.92	0.71	0.56	0.20

In the same table, Z_0 values are also listed for comparison. From tab.3 it can be found that Z_2 increases with the decrease of R_L=R_C. It can also be found when Z_2 is equal or less than 20 MΩ, Z_2/Z_0 is higher than 90%, indicating that the feedback effect by A5-1 is less than 10%; However, when Z_2 is » 20 MΩ, Z_2/Z_0 will decrease significantly, this is a priori

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due to the feedback effect via A5-1 and in other words, even though relatively small, the feedback effect becomes non-negligible.

By using the input impedance Z_2 = 18.5 MΩ (with R_S = R_L = 50 mΩ), the voltage gain $A_{V0} \approx 1.56$ of the "readout chain 2" at 1 MHz as a function of the signal impedance R_s can be drawn as shown in Fig.6.

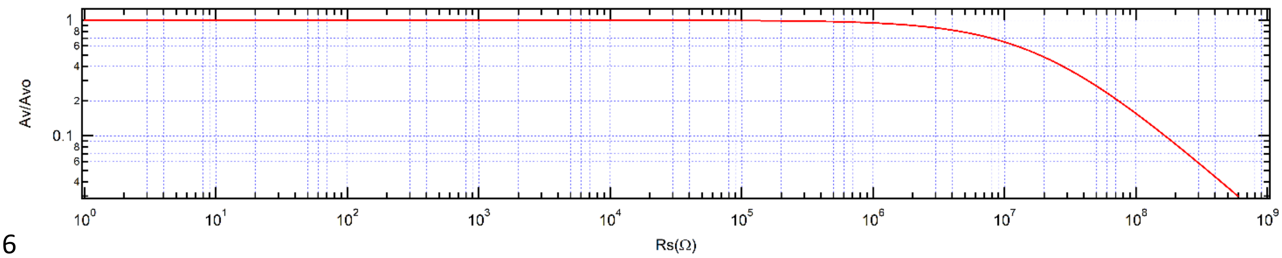

Fig.6

Fig.6 shows that with the increase of 1 MHz source signal impedance R_s, the actual voltage gain A_V of the "readout chain 2" at 1 MHz decreases. For $A_V \approx A_{V0}/\sqrt{2}$, the input impedance is as high as $R_s \approx 8$ MΩ.

3. Equivalent input noise estimation of the "readout chain 2":

The A5-1 input noise voltage at 1MHz is 0.25 nV/√Hz, with a voltage gain of 1.56, and its output noise voltage is 0.39 nV/√Hz.

The SA-230F5 input noise voltage is 0.25 nV/√Hz and the input noise current 5 pA/√Hz, so that the total noise voltage at its input is

$$\sqrt{(0.39nV/\sqrt{Hz})^2 + (0.25nV/\sqrt{Hz})^2 + (36\Omega \times 5pA/\sqrt{Hz})^2} = 0.50nV/\sqrt{Hz}$$

The input noise voltage of "readout chain 2" is 0.32nV/√Hz. The noise current of the LT-amp is not considered.

4. A similar "readout chain 2" used in experiments

It can be found results in LT-STM (low temperature Scanning Tunneling Microscope):

https://doi.org/10.1063/1.5043267

https://doi.org/10.1038/s41567-018-0300-z

https://doi.org/10.1126/science.abe3987

5. Remarks:

The input impedance of a readout chain with an *RLC* resonator depends greatly on the feedback of the LT-amp A5-1. Simulation results are partially verified experimentally and show that "readout chain 2" has less feedback effect and higher input impedance unlike "readout chain 1". Due to the complex phase components, it is difficult to predict the feedback effect and the input impedance value by simple estimation, so a simulation seems necessary for every configuration.

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6. Experimental results

The experimental checking has been made by Freek Massee with his experimental setup by changing the input impedance of the RT-amp https://doi.org/10.1063/1.5043261, and he wrote: " please find attached a comparison between the NF SA-230F5 (50 Ohm input) and the NF SA-220F5 (1 MOhm input). Everything else (temperature, amplification chain, etc) is identical. Clearly, the 1 MOhm input results in an asymmetric and much wider resonance. The baseline noise is a factor 2 higher, which makes sense. The background noise with HEMT on, though, is much bigger than with the 50 Ohm input." (see Fig.7)

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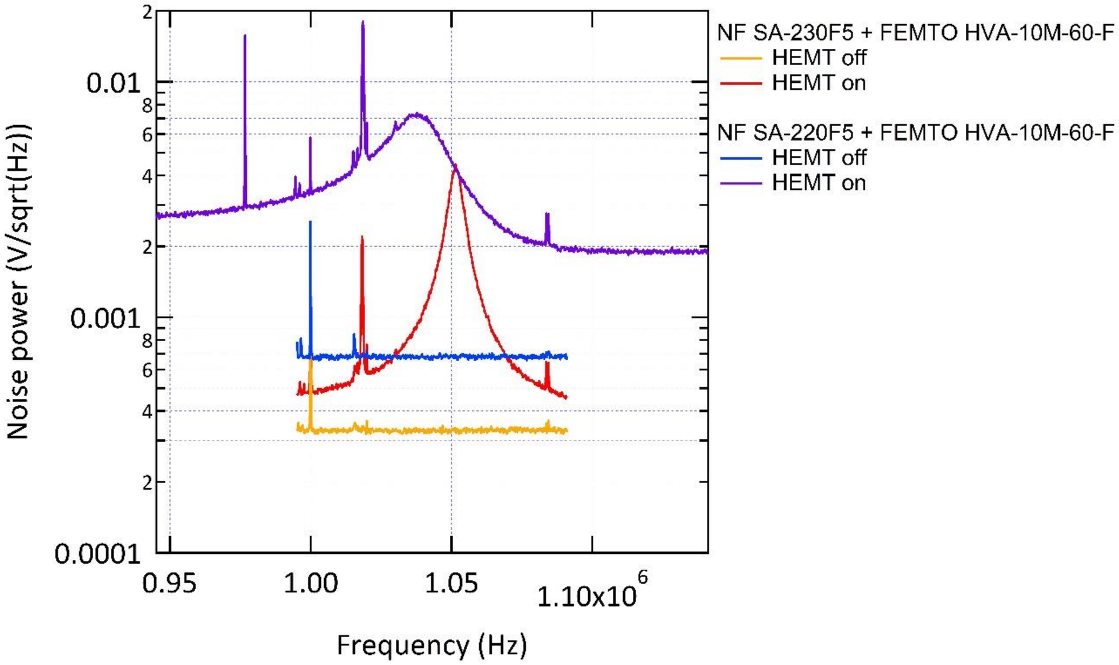

Fig.7

Final remark, the impedance matching between the output (50Ω) coaxial cable of the cryo-amp and the (50Ω) input impedance of the RT-amp can reduce the source signal distortion and its noise baseline. So, based on our simulation and experimental results in LT-STM MHz readout chain, the most beneficial effect of our HEMTs is to change weak and high impedance source signals at deep cryogenic temperature into robust signals, then they can be processed by electronics at room temperature. On the other hand, a high gain cryogenic amplifier (followed by a 1MΩ input impedance RT-amp) could induce unwanted feedback on source signals

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