Report for INFN Summer Exchange Program at SLAC National Accelerator Laboratory

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Contents

1 Introduction

This is a report of my work at SLAC under the INFN Summer Exchange Program for 2018. I worked in the CDMS collaboration, which is currently preparing the SuperCMDS Snolab experiment. CDMS aims at finding a WIMP-type dark matter candidate in the low mass range. SuperCDMS Snolab should be sensitive enough to eventually detect the neutrino floor if no signal is found.

My principal supervisor was Tsuguo Aramaki. I helped in three indipendent activities:

- measure the mechanical tension of certain wires using only the detector circuit without additions;
- compute numerically the electric field in a new type of detector;
- check a new type of cables.

I report only on the first, since the others were only to fill in dead times of the tension measurement.

2 Tension measurement

The SuperCDMS detector is made up of modules which consist of semiconductor cylinders with sensors on the top and bottom face (see Figure 1). An electric potential is applied between the two faces. There are two type of modules: iZIP (interleaved Z ionization phonon) and HV (high voltage). Both have phonon sensors, while only iZIP has ionization readout because the high polarization potential of HV provokes saturation of the signal.

The ionization signal of the iZIP is amplified by a HEMT (high electron mobility transistor), which is a low-noise transistor that works at cryogenic temperatures. The path from the iZIP module to the HEMT is of particular importance for the noise, thus it is made with a non-standard ad-hoc coaxial cable. This coaxial cable consists of a thin niobium-titanium superconductive wire tensioned in vacuum inside a copper cavity. The (relatively to usual)

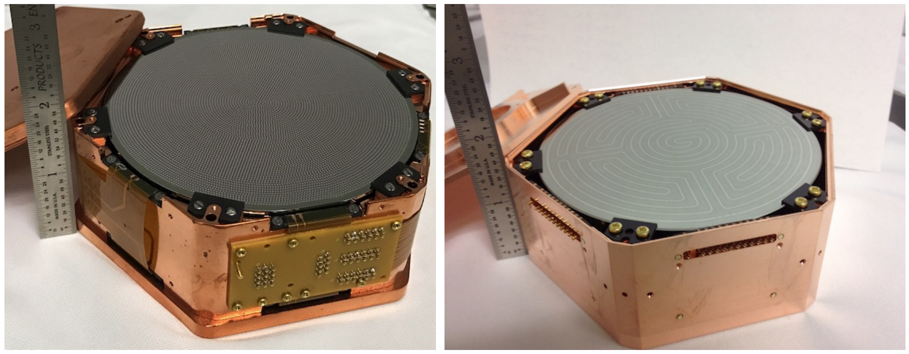

Figure 1: HV-type detector module (left) and iZIP-type (right), inside their exagonal housings.

small inner diameter, large outer diameter, and absence of dielectric provide a small capacitance and a large inductance which couple well with the detector and HEMT impedance chacteristics. Also, the dielectric would cause a vibration noise called triboelectric effect. The superconducting wire is thermally insulating and so avoids heating up the detector (the HEMT is at higher temperature).

In the previous iteration of the experiment (SuperCDMS Soudan) there were problems with these wires: they were suspected to have lost tension and touched the copper cavity. So a way to check the tension of the wires is desired for SuperCDMS Snolab.

2.1 Measurement with magnet

In general the tension of a conducting wire can be measured by applying a magnetic field and running an alternating current through the wire.[1] Since there is an alternating current, the magnetic field will exert an oscillating force on the wire. The motion of the wire in the magnetic field will then generate an electromotive force along the wire which can be easily measured. As a function of the vibration frequency, the e.m.f. will show a resonance peak at the natural oscillation frequency of the wire. The tension T is then related to this frequency f_0 via the formula

$$f_0 = \frac{1}{2L}\sqrt{\frac{T}{\mu}}, \tag{1}$$

where L is the length of the wire and μ is the linear mass density.

This measurement was already done two years ago by another summer student, Carlo Gilardi. He measured the resonance peak from room temperature and atmospheric pressure down to liquid nitrogen temperature (77 K) and vacuum. I had access to the same vacuum coaxial cable assembly he tested. The assembly is a long and thick rectangular copper plate with four grooves that host the wires. the grooves are covered by another copper plate. The wires are soldered on boards that provide electrical connection and keep them tensioned. The design geometrical parameters are: diameter of the wire 30.5 µm, depth of the groove 1.59 mm, width of the groove 1.50 mm.

I repeated quickly the measurement with the magnet at room temperature and atmospheric pressure to check the status of the wires. The circuit is the one in Figure 2, the same circuit used two years ago, even in magnets, resistance values and model of alternate current generator. I varied the source frequency in steps of 1 Hz. The data is reported in Figure 3, along with original Carlo's data.

I fitted the data with a forced harmonic oscillator model:

$$\ddot{x} + 2\gamma\dot{x} + \omega_0^2 x = F e^{i\omega_F t}, \tag{2}$$

where the real part of x is the lateral displacement of the wire (let's say at the center), ω_F is the angular frequency of the alternating current source, ω_0 is the angular natural oscillation

[1] M. Atac, M. Mishina, *A sensitive and simple method for measuring wire tensions*, Fermilab TM-1125.

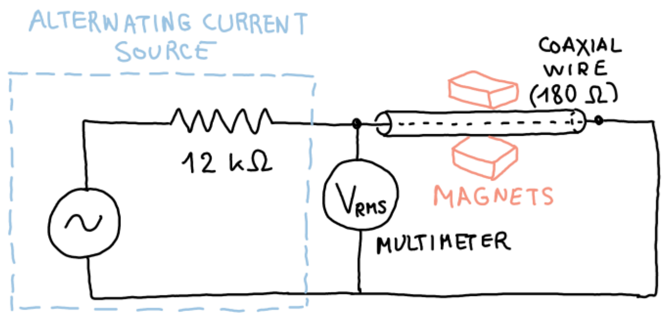

Figure 2: Circuit used to measure the resonance frequency of the wire in the coaxial cable.

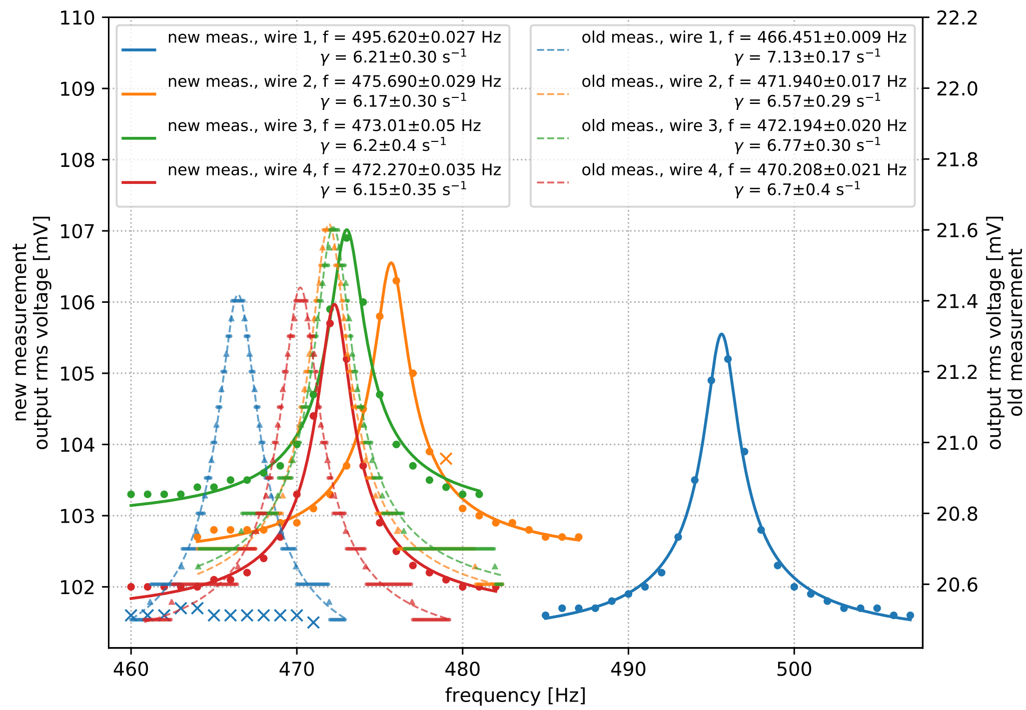

Figure 3: RMS voltage across the wire versus frequency of the alternating current through the wire. The data (dots) is fitted (lines) with the amplitude of formula (5). Continuous lines are for data taken this summer (left y-axis scale), while dashed lines are for data taken two years ago (right y-axis scale). For old data, the fit is made on the midpoints of the steps in the data (triangles in the plot), because the data has low dynamical range but finely spaced x-points. The fit is least squares; the uncertainties are taken uniform and estimated imposing that $\chi^2/\mathrm{ndof} = 1$. In the legend the two significative parameters of the fit are reported: the frequency of the resonance $f = \omega_0/(2\pi)$ and γ.

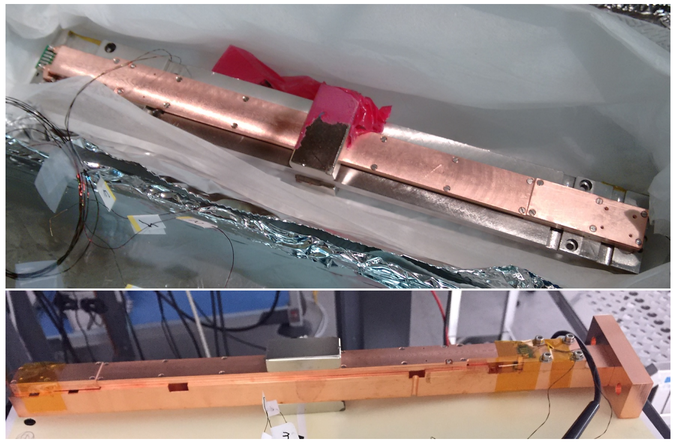

Figure 4: Photo of the coaxial cables assembly from two years ago (top) when the resonance frequency was measured at room ambient conditions, and of the same assembly from this summer (bottom). The assembly is mounted on a different base.

frequency of the wire. The result for x is

$$x(t) = \frac{F}{\sqrt{(\omega_F^2 - \omega_0^2)^2 + (2\gamma\omega_F)^2}} e^{i\omega_F t}. \tag{3}$$

The force exerted by the magnetic field on a charge in the wire along the direction of the wire is

$$F_q = q v_{\text{osc}} B_\perp, \tag{4}$$

where q is the charge, v_{osc} its speed component due to the oscillation of the wire, $B_\perp$ the magnetic field component perpendicular to both the wire and the direction of oscillation. So the e.m.f is[2]

$$V = \frac{\langle F_q \rangle}{q} L = \langle v_{\text{osc}} B_\perp \rangle L \propto \dot{x} \propto \frac{\omega_F}{\sqrt{(\omega_F^2 - \omega_0^2)^2 + (2\gamma\omega_F)^2}} e^{i\omega_F t}, \tag{5}$$

where L is the length of the wire and the average is along the wire.

From Figure 3 we see that the resonance frequencies of the wires changed. We first exclude that the difference is due to the setup; the possible sources of differences that came to my mind are:

- I ran a current five times larger through the wires. If the wire heats up because of the current, it will dilate and loose tension, yielding a lower resonance frequency.
- The ambient temperature may be different. The thermal expansion of copper is greater than that of niobium-titanium, so the tension increases with the temperature.
- I put the magnets in a slightly different position. A difference in the magnetic field is expected to have little influence on the resonance frequency.

The first two effects would make the same contribution to all the wires. The last one could be a bit different, but have to respect the simmetry of the setup, so the effects on wire 1 and 4 should be the same and also for 1 and 2. The displacements of the peaks from the old data are all quite different, so I conclude they are not due to the setup. In a photo of the old measurement (see Figure 4) we can see that the assembly was mounted on a different base, so it may be that tightly screwing the assembly on another base changed the tension.

[2] The potential difference on the wire also changes because the e.m.f. of the magnetic field changes the current flowing on the wire, since the current source is not ideal, but it is a small correction.

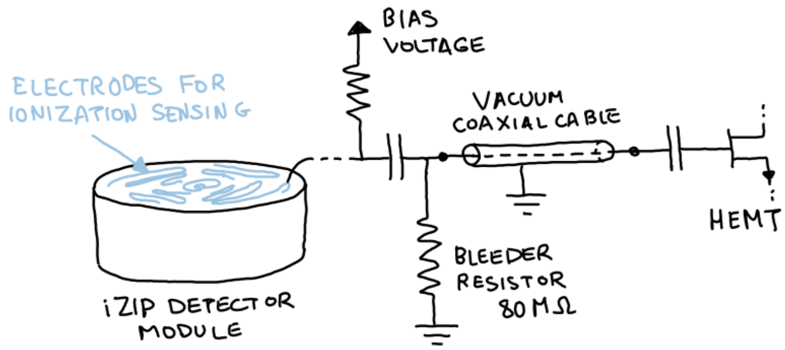

Figure 5: Ionization readout circuit in the detector.

2.2 Measurement with the detector circuit

The vacuum coaxial wire is electrically connected only to the ionization readout electrodes through a capacitor, to the HEMT gate (also through a capacitor) and to ground with a 80 MΩ resistor (see Figure 5). Adding a switch to run a large alternating current through the wire would significantly increase the noise. Putting a magnet near the wire is also a problem, because a permanent magnetic field would disturb operation of SQUID chips that read the phonon signal, and increase the vibration noise, while an electromagnet may add noise to the environment even when shut off, and would require a change of circuit design that is a problem at this stage of preparation.

Dismounting the core components from the detector is a long and delicate process, so putting out the coaxial assembly only for routine checking is not admissible. The method for measuring the resonance frequency of the wire outlined in the previous subsection is thus not applicable.

The wire can still be made to vibrate by vibrating mechanically all the detector from outside (an audio speaker attached on the detector is sufficient for this purpose), but the electrical effect of the vibration has to be measured with the detector circuit. The detector is shielded from magnetic fields, and the bleeder resistor that connects the wire to ground keeps the charge on the wire to zero. The wire is completely superconducting, so the temperature gradient on the wire should not induce a charge if there is no current flowing through. Ideally this means that the vibration would not induce electrical effects. Still, one hopes that some very small coupling exists, and that it can be exploited to find a resonance peak.

2.2.1 Test setup

Here at SLAC there are two cryogenic test facilities for CDMS. The newer, and most similar to the final detector, was occupied with higher priority tasks, and the operation of the other had to be stopped because it was a source of noise (they are in the same cleanroom), so of 35 working days, I could take data only on 8 days. The temperature of the fridge varied between 3.5 K and 15 K in our tests.

In the test setup there is only the vacuum coaxial assembly and the HEMTs with their biasing circuit (see Figure 6). The cryogenic fridge can be vibrated with a loudspeaker. The output of the HEMT is further amplified, and I can read it with an oscilloscope or a spectrum analyzer (model SRS785). I can generate the signal for the speaker either with a signal generator or with the internal source of the spectrum analyzer. Since the time base of the source of the spectrum analyzer is the same of its ADC, I preferred tipically to use the spectrum analyzer for everything.

The spectrum analyzer passes the input through an analog antialiasing filter, the cutoff frequency of which is less than the sampling rate of the ADC. The input fullscale is changed analogically before the ADC to use the full dynamical range. To compute an FFT up to frequencies less than the full span, the ADC samples pass through a digital antialiasing filter and get decimated. On the FFT output a factory calibration is applied and the effect of antialiasing filters is corrected.

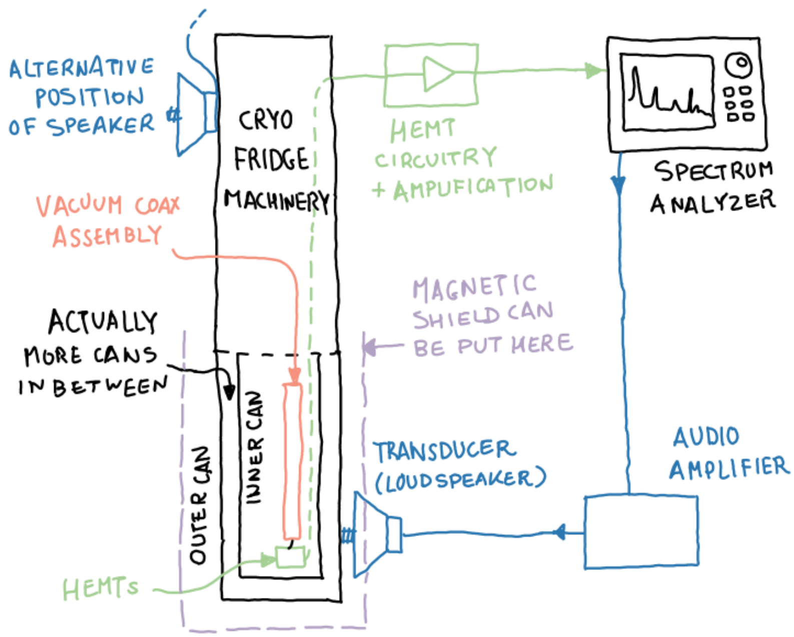

Figure 6: Test setup for the measurement of resonance frequency of vacuum coaxial wires directly with HEMTs as in detector circuit.

The duration of acquisition needed for a certain spacing of the FFT frequencies is the inverse of the spacing. The acquisition can be started by a trigger or as the previous one ends. A root mean square average of the last N FFT amplitudes can be computed, or a vector average on the complex values to suppress the part of the signal that is not coherent between acquisitions.

We search for the effect of the vibration of the wire both by looking at an FFT of the output without inducing vibration with the speaker and by looking at the response under different forced vibration frequencies.

2.2.2 First measurement (without bleeder resistor)

The first time we used the apparatus we didn't had much time (only one day and a half). We had available an assembly which is not the one used two years ago; the tension of these wires is greater. We still didn't had a board to connect the bleeder resistors—specialized wire-bondings are needed since standard resistors do not work at cryogenic temperatures—so we tested without them. Furthermore, only one of the HEMTs was working.

Without the bleeder resistor, static charge can accumulate on the wire. The movement of the wire inside its copper housing changes the capacitance of the coaxial cable, so if there is charge a varying e.m.f. is induced on the wire. This means that seeing the effect should be easier.

Indeed, we quickly noticed a peak at about 466 Hz, even without vibrating the fridge. Vibrating the fridge at 466 Hz increases the height of the peak. After stopping the vibration the peak gradually goes down; we expect the decay speed of a thin vibrating wire in vacuum to be somewhat large. I did not model the decay time of the wire vibration, but intuitively it should be larger than that of a guitar, so at least some seconds.

To measure the decay time we measured the height of the peak during vibration, and then the rms average height during a period of 10 s after the vibration is shut off.[3] The amplitude of an harmonic oscillator decays as

$$x(t) = x_0 e^{-\lambda t} \tag{6}$$

[3] Taking an average is not the obvious thing to do and complicates things. In fact, I had never used the analyzer before and just used it as it was configured.

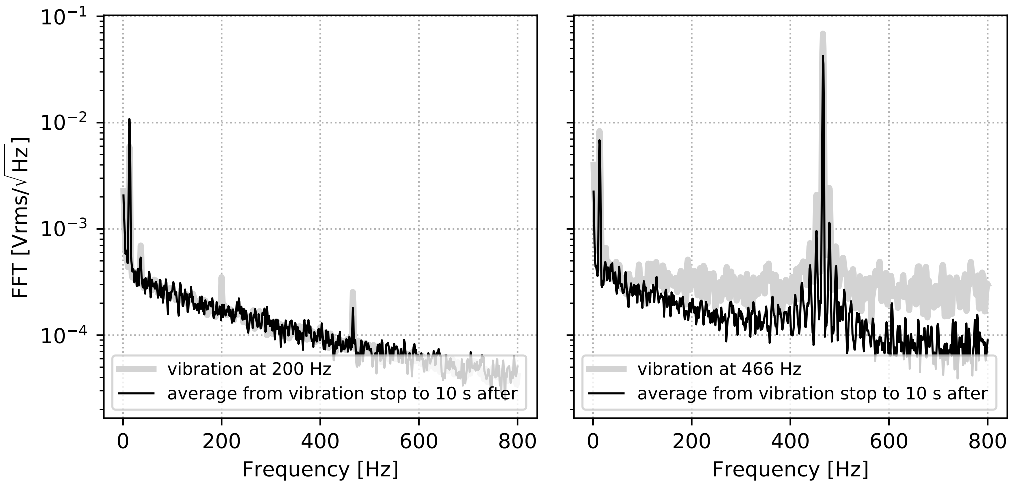

Figure 7: Spectrum of HEMT output during vibration (light gray line) and averaged from the moment the vibration stops to $10\,\mathrm{s}$ after (black line), with vibration frequency $200\,\mathrm{Hz}$ (left) and $466\,\mathrm{Hz}$ (right). Note that the $466\,\mathrm{Hz}$ peak is visible also in the left panel. The FFT spacing is $1\,\mathrm{Hz}$. The speaker is mounted on the bottom of the fridge can. The source amplitude is $0.6\,\mathrm{V_{pp}}$ at the input of the audio amplifier, whose input level knob is set to MAX. The source is a SRS DS345 waveform generator.

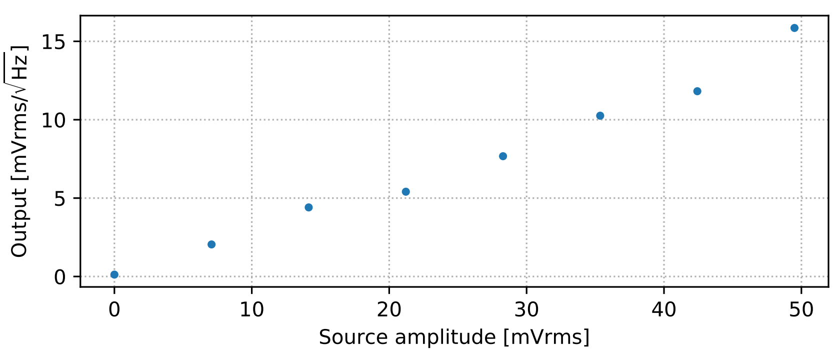

Figure 8: Height of the peak at $466\,\mathrm{Hz}$ versus vibration driver source amplitude. The setup is the same of the data in Figure 7.

and we are measuring x_0 and

$$x_1 = \sqrt{\frac{1}{T}\int_0^T \mathrm{d}t\, x^2(t)} = x_0\sqrt{\frac{1-e^{-2\lambda T}}{2\lambda T}} \tag{7}$$

with $T = 10\,\mathrm{s}$. The data is in Figure 7. For vibration at $466\,\mathrm{Hz}$, solving (7), we obtain $\gamma = 0.12\,\mathrm{s}^{-1}$.

For cross check we repeated the procedure for $200\,\mathrm{Hz}$ (also reported in Figure 7) and $650\,\mathrm{Hz}$. For those frequencies the peak returns to the noise floor too quickly to measure the decay time. I also checked the relation between the speaker source amplitude and the height of the peak, which I expect to be linear. This data is in Figure 8. Unaptly, I checked up to an amplitude lower than the one used for measuring the decay time.

The nominal tension of the wire when mounting is $40\,\mathrm{g}$. Using formula (1) and

$$\Delta T = EA\left(\left(\frac{\Delta L}{L}\right)_{\mathrm{Cu}} - \left(\frac{\Delta L}{L}\right)_{\mathrm{NbTi}}\right), \tag{8}$$

where ΔT is the variation in tension due to temperature, E is Young modulus, $\Delta L/L$ is the linear thermal expansion, A is the section area of the wire, and using the numerical

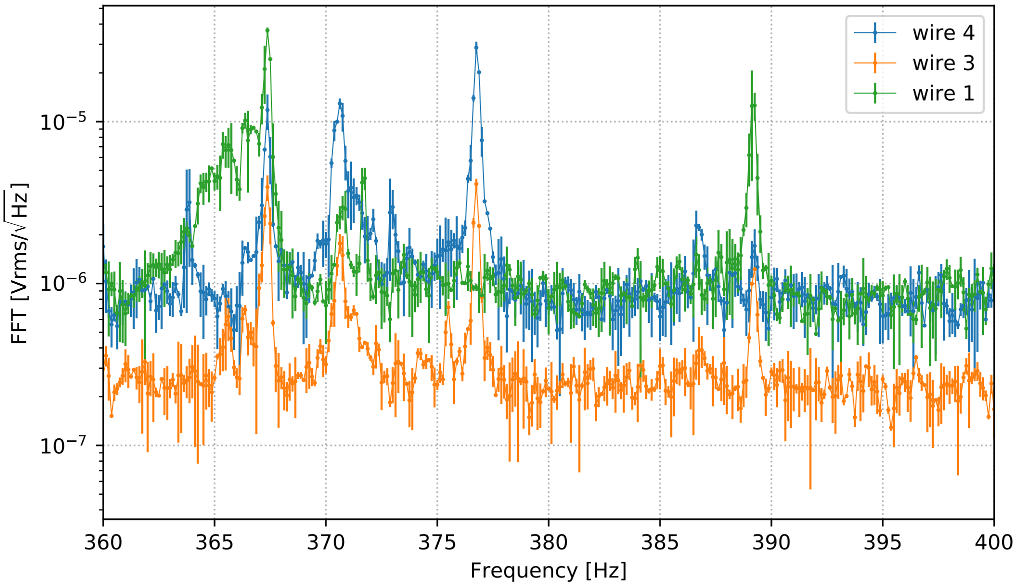

Figure 9: Spectra of the HEMTs output without forced vibration. Each spectrum is obtained with two RMS averages of 4 acquisitions each, frequency-per-frequency their mean is taken as the estimate and their sample standard deviation (difference over $\sqrt{2}$) as the uncertainty. The FFT frequency spacing is $1/8\,\mathrm{Hz}$. Note: the wires are not the same of Figure 7 (see text).

values $L = 26.6\,\mathrm{cm}$, $A = 7.31 \times 10^{-10}\,\mathrm{m}^2$, $E = 7 \times 10^{10}\,\mathrm{N\,m^{-2}}$, $(\Delta L/L)_{\mathrm{Cu}} = -0.326\,\%$, $(\Delta L/L)_{\mathrm{NbTi}} = -0.151\,\%$, $\rho_{\mathrm{NbTi}} = 5.7\,\mathrm{g\,cm^{-3}}$, I obtain $f_0 = 493\,\mathrm{Hz}$.

2.2.3 Measurement with bleeder resistor

We got bleeder resistors on a board and the assembly used two years ago, the one tested in subsection 2.1, and also a board with all HEMTs working. Apart from that, the setup is the same described in the previous section (Figure 6). It turns out that the HEMT that should be connected to wire 2 is probably disconnected, so we measure only for wires 1, 3, 4. I also disconnected two fridge cables which provided part of the cooling and temperature readout because they were a significative source of noise. Between whiles I momentarily reconnected the cables to check the temperature. For driving vibration I always used the analyzer internal source.

From the old data we know that the resonance frequencies of the wires at 77 K are about 380 Hz, from 77 K to 4 K I estimated it should decrease by $\sim 1\,\mathrm{Hz}$. So we are searching for peaks in the neighboorhood of 380 Hz. In Figure 9 the spectra without forced vibration are reported. Then, sweeping the vibration frequency, I measure two things:

1. The steady height of the peak at the vibration frequency during vibration (Figure 10). I measured this manually taking an FFT at each vibration frequency for wires 4 and 3 and I used an automatical function of the analyzer to sweep and measure for wire 1.

2. The decay time of the peak (Figure 11), measured as the speed of descent $S = -\gamma \cdot (20/\log(10))\,\mathrm{dB}$ (so S has units dB/s). I measure this manually by setting the analyzer units to dB and writing down the value after a known time. This way of measuring the decay time sometimes does not work because the marker will automatically move to a neighbor frequency bin, or because for a frequency close to a slowly decaying peak the vibration peak will drop under the other peak shoulder too fast (the acquisition time is 1 s).

Then I checked linearity in the response to the source amplitude at various frequencies (Figure 12), both on peaks of the spectrum and on the noise floor, with the speaker in the top mounting position. I observe that there is a knee on all series at the same source

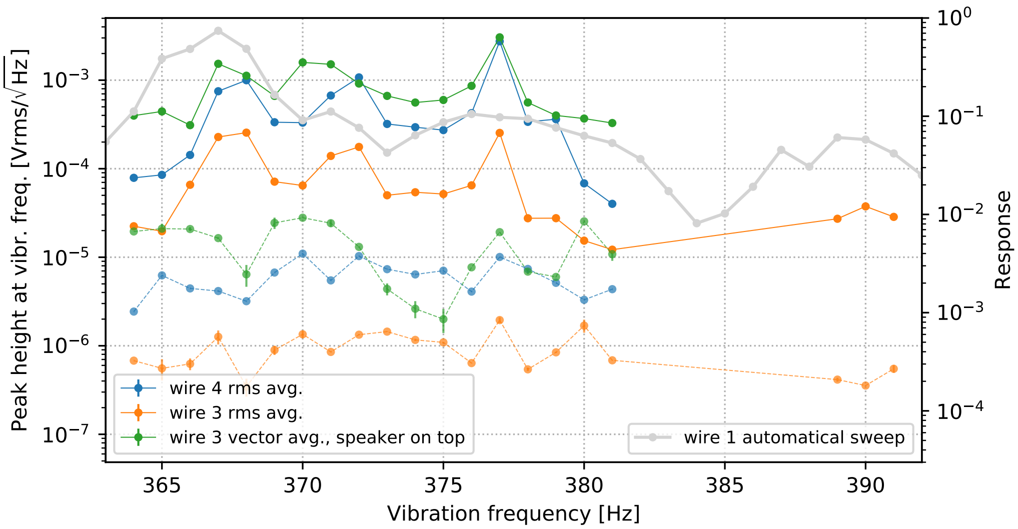

Figure 10: Response of the HEMT output to vibration. For wires 3 and 4 (left legend, left y-scale) the response is measured by manually setting the vibration frequency, waiting for the effect of the previous frequency to decay, taking the average of 4 FFTs with $1\,\mathrm{Hz}$ spacing and taking the value at the vibration frequency. For wire 3 data an uncertainty is assigned with the same procedure of Figure 9. The dashed lines are the response at double the vibration frequency. For wire 1 (right legend, right y-scale) a similar procedure is operated automatically by the analyzer, with a settle time of $20\,\mathrm{s}$ (time to wait between acquisitions) and an integration time of $10\,\mathrm{s}$ (frequency resolution $0.1\,\mathrm{Hz}$, a more sensible setting would have been $1\,\mathrm{s}$). In this case the output is the amplitude divided by the source amplitude. The source amplitude was $100\,\mathrm{mVrms}$ for wires 3, 4 and $3.53\,\mathrm{mVrms}$ for wire 1. For the measurements labeled "rms avg" in the legend, the speaker was in the bottom mounting position, while for the other two in the top one.

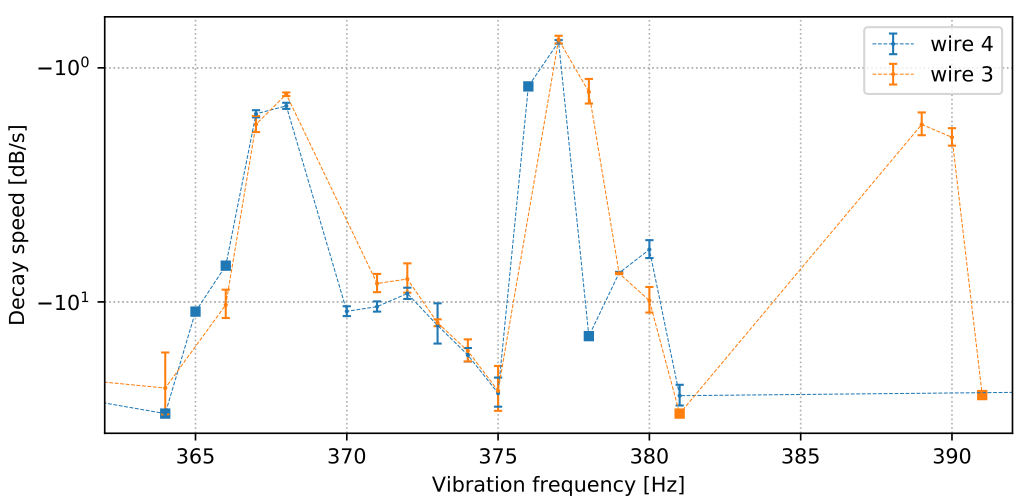

Figure 11: Decay speed of the vibration peak after vibration is shut off. The decay speed S is related to the damping factor γ by $S = (-20/\log(10)\,\mathrm{dB}) \cdot \gamma$. The decay speed is measured by looking at the analyzer screen and writing down the variation in height of the peak in a known time. The procedure is repeated for various time intervals and then the mean and sample standard deviation of the mean are taken. The boxes are points for which only one measurement is done so there is no uncertainty estimate.

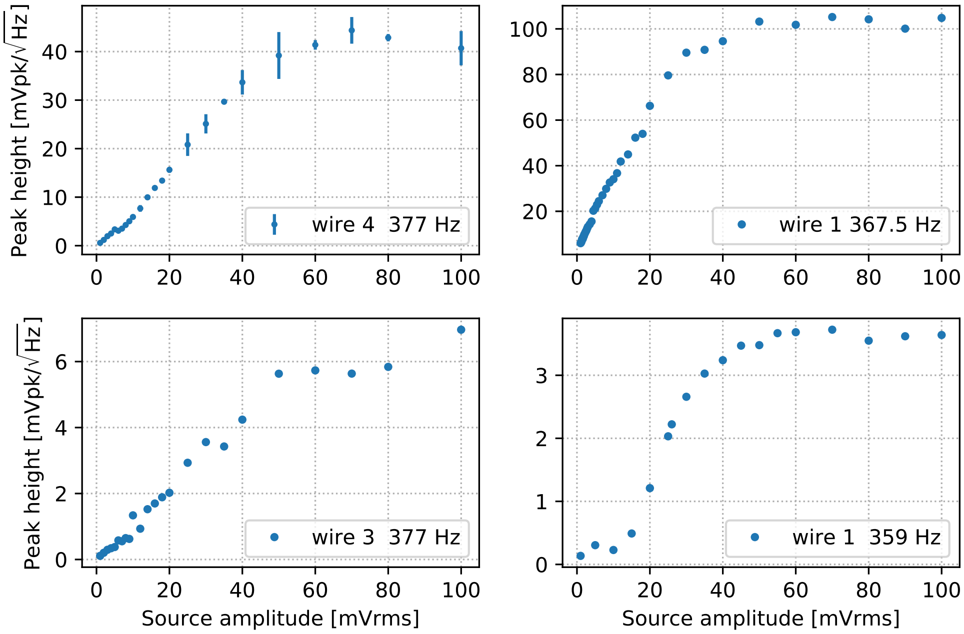

Figure 12: Height of the peak at vibration frequency in the HEMT output versus amplitude of the vibration driving source. For the upper and lower left plots the frequency is on a prominent peak of the spectrum, while for the lower right it is on the noise floor (see Figure 9 and Figure 11 for reference). For the wire 4 series, an estimate of the uncertainty made by repeating each measurement two times is given. The speaker is in the top mounting position.

amplitude, so I suppose it is due to the coupling of the speaker to the fridge: while in the bottom position there is a proper mounting screw, on the top one it was tied with some tape and an ethernet cable.

From this data we concluded we could not find the wire resonance peaks. The most promising peaks are the ones with larger decay time (for the clearer measurement in subsubsection 2.2.2, $\gamma = 0.12\,\text{s}^{-1} \to S = -1.0\,\text{dB/s}$), the ones at about 367 Hz and 377 Hz, but we would expect each wire to have his own different peak, while the 367 Hz peak is shared by all three wires and the 377 Hz by two of them.

2.2.4 Again without bleeder resistor

We opened the cryogenic fridge, disconnected the bleeder resistor, and left everything else as it was for the measurement described in the previous subsubsection. While taking data, in addition to disconnecting temperature readout cables, we turned off the pulse tube of the fridge. Since without bleeder resistor the wire resonance peak should be more visible, we hoped to discover if the resonance peak was there in the previous data.

The first thing we noticed was that the 377 Hz and 367 Hz were gone. By sweeping quickly the vibration source frequency, I could not notice any slowly decaying peak in the spectrum of wire 3. But insisting on a small peak[4] that apparently did not even show a significative response to the vibration, we observed the height of the peak oscillated very slowly (about 1 min period) but by significative amplitude. We then found another peak with the same behavior for wire 1.

We took an high resolution spectrum centered on each of these peaks (Figure 13), with the vibration shut off. We observed that each of them was actually two narrow and close peaks, so probably the beat of the height was due to this structure. I took videos of the peaks on the screen with lower FFT resolution (1 Hz) to observe their behaviour with time. From a first estimate, the beat period is compatible with the inverse of the frequency difference

[4] I must thank my supervisor Tsuguo for his stubborness in insisting on this peak.

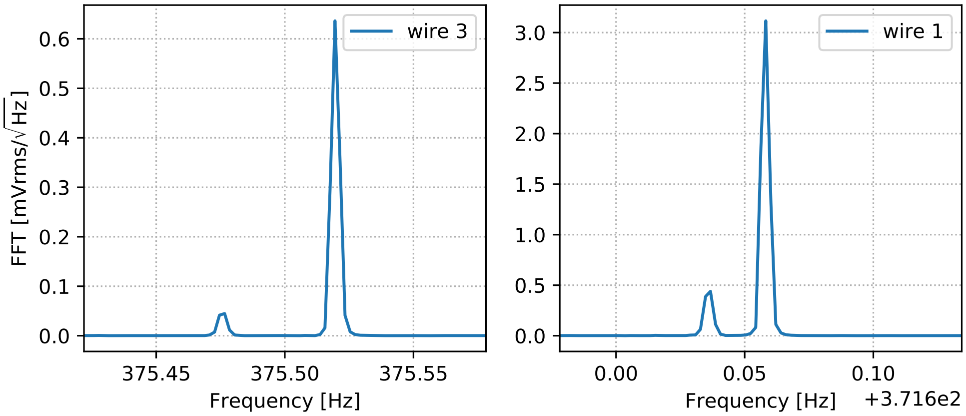

Figure 13: Spectrum of the HEMT output for wires 3 and 1 without forced vibration, with bleeder resistor disconnected, zoomed on two peaks with particularly slow decay time. The FFT spacing is $1/512\,\mathrm{Hz}$. Note that the y-scale is linear.

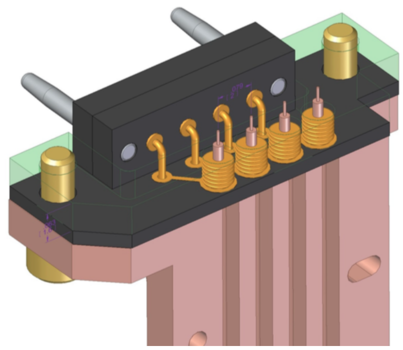

Figure 14: Illustration of wires on one end of the coaxial cable for the assembly used in subsubsection 2.2.2.

between the peaks, and the decay time, around $10\,\mathrm{min}$, is compatible with $1/\gamma$ obtained from the width ($\mathrm{HWHM} = \sqrt{3}\gamma$).

Supposing these peaks are the resonance peaks of the wires, we have to answer two questions:

1. Why was the decay time in the wire from the other assembly about 50 times shorter?
2. Why there is a fine frequency splitting?

For the first question, we first have to take into account the variation of γ as the wire is tensioned. I suppose the quality factor ω_0/γ should remain the same, because the wire undergoing the same trajectory will dissipate the same fraction of energy, so this effect only accounts for a $466\,\mathrm{Hz}/375\,\mathrm{Hz} = 1.2$ shorter decay time. The other possible explanation is that the higher tension wire is also assembled in a different way: instead of being soldered at ends, one of the ends passes through a bellow and cannot come unstrung because of a blocking cylinder fixed on the wire (see Figure 14). This may account for higher dissipation due to the movement and friction of the cylinder on the bellow, but I can not make a quantitative prediction.

The second question is easily solved if we allow for a little anisotropy in the plane perpendicular to the wire, which is plausible considering that the wire is soldered on both ends over circuit boards. There are two eigenmode directions of oscillation with slightly offset frequencies, and our speaker was not inducing vibration precisely in one of these two directions, so we had both frequencies in the spectrum.

The most important fact is that the peaks, at frequency $375.52\,\mathrm{Hz}$ for wire 3 and $371.66\,\mathrm{Hz}$ for wire 1, are also present in the data with bleeder resistor: they can be spotted in Figure 9. I did not found a peak for wire 4, but my supervisor managed to after I had already stopped going in the laboratory due to the close end of my working term.

2.3 Conclusions

We managed to find the resonance peaks of the wires when the bleeder resistor was disconnected, but not when the resistor was connected, as it is the detector. However, we proved we could have detected the resonance peak if knowing where to look. Moreover, now that we know the peak height will not react to vibration by increasing almost immediately, but by slowly going up because of the beat between the eigenmodes of the wire when the FFT spacing is larger than their separation, and we know what decay time to expect, we could probably spot the resonance peak even without having the precise location. Anyway, any assembly has to be tested before going in the detector, so it could be arranged that the resonance frequency is measured without bleeder resistor if it turns out still too difficult to find it directly.

Also, if the eigenmodes directions turn out to be the ones orthogonal and parallel to the assembly plane (so the same for any assembly), vibrating in one of those directions may remove the beat problem and ease the task of finding the peak. Another way of getting rid of the beat is to have a frequency spacing of the FFT small enough, but on a large span which is not attainable with the spectrum analyzer I used. Probably this can be accomplished with a commercially available DAQ.

A problem that has to be studied further is that, since with didn't sufficient tests with magnetic shielding, we don't know if the the resonance peak can be detected with bleeder resistor *and* no magnetic field.

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