

# Development of a superconducting thin-film Nb-coil: for use in the miniGRAIL transducers

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In this paper the development of a thin-film Nb-coil to be used in the transducers for miniGRAIL will be discussed. Measurements of the quality and workings of the coil will be given and the necessary theory will be discussed. The latest developments will be shown including designs of new experiments.

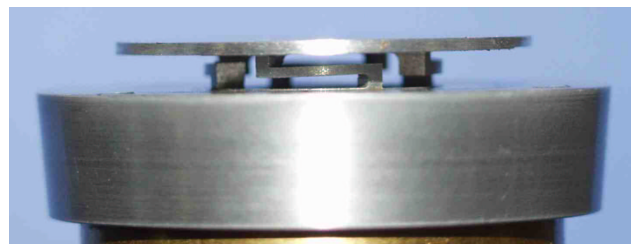
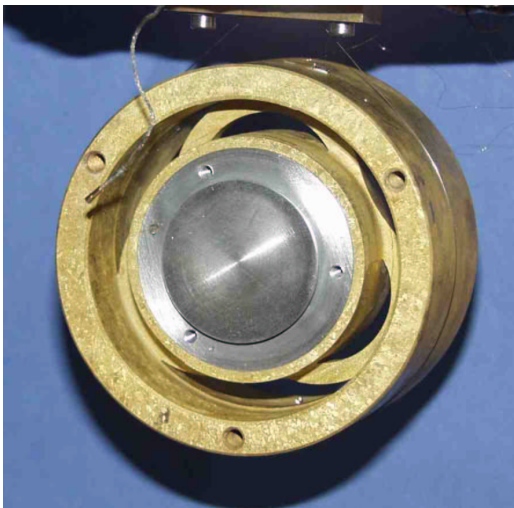
## I. INTRODUCTION

This paper is the conclusion of a 1 year stage in the QV3-group at the Kamerlingh Onnes Laboratorium and is part of a physics graduate education. It describes the development of a thin-film superconducting coil to be used in the miniGRAIL-project[1].

## II. MINIGRAIL

A cryogenic resonant-mass gravitational wave detector has four main components. A (big) detector mass, vibration isolation, cooling systems and transducers. MiniGRAIL is such a detector, it consists of a 65 cm diameter spherical antenna made of CuAl(6%) alloy with a mass of 1150 Kg and a resonance frequency of 3250 Hz. It's vibrational isolation is done by seven 140 Kg masses and the complete detector is placed on a 'quiet' surrounding. The antenna will be operated at 20 mK and is cooled by a dilution refrigerator. The six transducers on the antenna allow for detection of a gravitational wave on a bandwidth of  $\pm 230$  Hz, and give the ability to locate the direction of from which the wave originated. The sources miniGRAIL is aiming at are for instance, non-axisymmetric instabilities in rotating single and binary neutron stars, small black-hole or neutron-star mergers.

The transducers consist of a two stage mechanical amplifier (two spring-mass systems) and an electrical amplifier. A thin-film coil will be used in combination with a dc-SQUID[2] to detect offset from equilibrium in the mechanical amplifiers. The mechanical amplification will be done by the resonators shown in figure 1. They are a '4-arms AL5056 resonator with a small mass on top of a larger mass separated by 4 s-shaped springs. Ont top of the small mass there is a film of sc material. The 2d is a small mass inside a bigger mass separated by springs The '4-arms' amplifier will be fitted into the rosette amplifier by shrinking it with liquid nitrogen and the combined two-mass system is to be



AL5056-resonator(4-arms resonator) sideview

CuAl6-resonator(rosette resonator) with AL5056 resonator inside

FIG. 1: Mechanical resonators

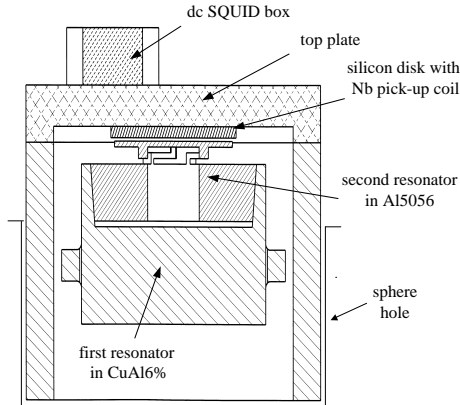


FIG. 2: Schematic setup assembled transducer

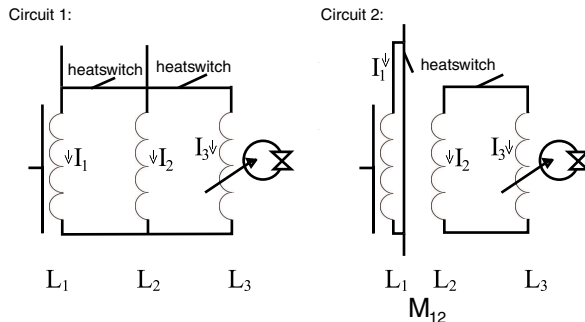


FIG. 3: Possible coupling circuits between the squid (right size of circuit) and the mechanical resonators (left side of the circuit)

fitted into the spherical mass with the same technique[3]. The complete transducer is schematically shown in figure 2.

### III. THEORY

The movement of the mechanical resonator has to be translated into a current. This can be done with a capacitance or inductance measurement (other non-resonant measurements are possible). For miniGRAIL an inductive measurement was chosen and no other readout-system will be discussed here[4]. A thin-film Niobium coil in front of a niobium thin-film on top of the ‘4-arms’ Al5056 resonator carries a current which creates a magnetic field between the coil and the surface. When the resonator moves the gap between the coil and the resonator will change, and the magnetic field will change as a result of this. The change in magnetic field induces a current in the coil which is measured with a DC-squid coupled to the coil with one of the circuits shown in figure 3 In circuit 1 the current through the squid coil caused by a change of the gap can be calculated using the flux-law (initial values  $I_1 = -I_2$  and  $I_3 = 0$ ):

$$I_3 = \frac{L_1^0 L_2^0 I_1^0 \frac{x}{d}}{L_1^0 (1 + \frac{x}{d})(L_2^0 + L_3^0) + L_2^0 L_3^0} \quad (1)$$

Where  $L_2(x) = \text{constant} = L_2^0$ ,  $L_3(x) = \text{constant} = L_3^0$  and  $I_1^0 \equiv I_1(x = 0)$ ,  $L_1(x) = L_1^0 (1 + x/d + O(x^2))$ ,  $x$  is the deviation of the surface from its initial position and  $d$  is the size of the gap between the coil and the surface when  $x = 0$ . A Taylor-expansion of this result gives:

$$I_3 = \sigma L_1^0 L_2^0 I_1^0 \frac{x}{d} \quad (2)$$

with  $\sigma = (L_1^0 L_3^0 + L_2^0 L_3^0 + L_1^0 L_2^0)^{-1}$ . In circuit 2 a similar calculation can be done (initial values  $I_1 = I_1^0$ ,  $I_2 = I_3 = 0$  and after Taylor expansion):

$$I_3 = \frac{L_1^0 M_{12} I_1^0 \frac{x}{d}}{L_1^0 L_2^0 + L_1^0 L_3^0 + M_{12}^2} \quad (3)$$

with  $M_{12} = k_{12} \sqrt{L_1^0 L_2^0}$  the mutual inductance between coil 1 and 2. Since  $k_{12}$  will be approximately 1 both circuits are potentially equally sensitive.

The SignaltoNoise-ratio(SNR) in power is

$$\frac{S}{N} = \left( \frac{M_{3s} I_3}{\phi_N} \right)^2 = \frac{L_3^0 (k I_3)^2}{\phi_N^2 / L_s} \quad (4)$$

where  $L_s$  is the squid-inductance,  $M_{3s} = k_{3s} \sqrt{L_3 L_s}$  is the mutual inductance of the squid with the input-coil  $L_3$  and  $\phi_N$  is the squid noise. The SNR can be maximized by maximizing  $I_1^0, L_1^0, L_2^0$  and choosing the inductances in such a way that  $L_3^0 = \frac{L_1^0 L_2^0}{L_1^0 + L_2^0}$  (circuit 1) or  $L_3^0 = (L_1^0 L_2^0 + M_{12}^2) / L_1^0$  (circuit 2), which can be proven by differentiating equation 4 to respectively  $I_1^0, L_1^0, L_2^0$  and  $L_3^0$ . This SNR doesn't take into account the effects of backaction-noise of the squid to the resonator. Final optimization requires a more detailed analysis, but the SNR calculated above is enough for our purposes. The requirements of our system to achieve high sensitivity, accuracy and reliability are:

- optimal value's of inductances (large SNR)
- high critical current (large signal)
- small distance (large signal)
- work at ultra-low temperatures (high Q / reduce noise)
- a small dissipation of the persistent current (long time without trapping new current)

To be able to design a coil with the required inductance it is necessary to make an estimation of the inductance. Our coil will consist of broken circles connected to each other in such a way the current travels back and forth, and the width of each turn is constant and the same as the distance between two turns (a detailed explanation of the design will be given in chapter IV A).

As a model for our coil we will use  $N$  concentric rings with a current  $I_n = (-1)^n I_{coil}$  running in the  $n$ th ring, where  $(-1)^n$  is necessary to simulate the correct direction of the current. If we use the approximation  $d \ll w$ , where  $w$  is the width of a circle, then we have a situation where the magnetic field between the superconducting surface and the coil is constant in size and direction for each separate ring. The inductance of this system is

$$L = \sum_{i=1}^N L_i \quad (5)$$

$$L_i = I_i^{-1} \sum_{j=1}^i \Phi_j \quad (6)$$

where  $\Phi_i$  is the total flux trapped between winding  $i$  and  $i - 1$ .

Because this model uses a counterwound coil, the current in each subsequent turn is in the opposite direction of the previous and half the terms in calculating the inductance cancel each other leaving the following formula for L.

$$L = I_{coil}^{-1} \sum_{j=1}^{\frac{N}{2}} \Phi_{2j} \text{ when } N \text{ is even.} \quad (7)$$

$$L = I_{coil}^{-1} \sum_{j=1}^{\frac{N+1}{2}} \Phi_{2j-1} \text{ when } N \text{ is odd.} \quad (8)$$

When using a counterwound coil it is practical (but not required) to take  $N$  even which we will assume to be the case for the rest of the calculation. In our real counterwound coil, taking only half the terms means taking the area *enclosed* by the coil, which is what one expects for inductance calculation. The flux trapped by each turn

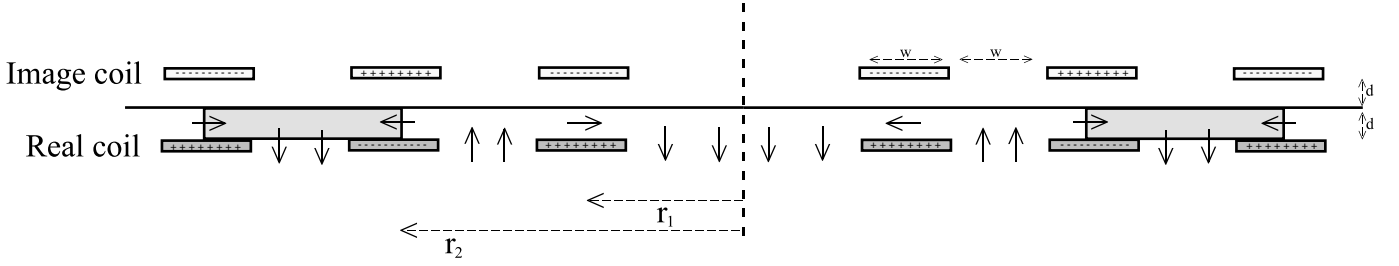


FIG. 4: Model of the flat coil used to calculate the flux

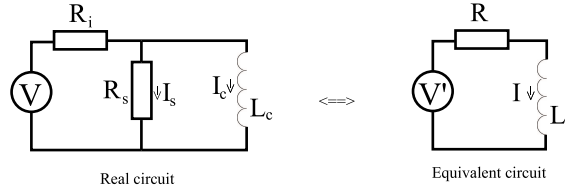


FIG. 5: Model-circuit for creating a persistent current

can be calculated by considering a cylindrical ring between the coil and the superconducting surface. The total flux through this ring must be zero (Ampere's law). The flux through the top is zero, through the sides it equals  $2\pi d(\vec{B}(\vec{r}_i) \cdot \vec{r}_i - \vec{B}(\vec{r}_{i-1}) \cdot \vec{r}_{i-1})$  thus the flux trapped by the coil is the opposite of this (figure 4).

$$\Phi_i = 2\pi d B(r_i + r_{i-1}) \quad (9)$$

Enter this into equation 7 with  $r_i = r_1 + 2w(i - 1)$ ,  $r_0 = 0$  and using  $B = \mu_0 I / 2w$  we find:

$$L = \frac{\pi \mu_0 d}{w} (r_1 N - 3wN + 4w \frac{N}{2} (\frac{N}{2} + 1)) \quad (10)$$

When  $w \ll r_1$  this can be simplified into  $L = \frac{\pi \mu_0 d r_1 N}{w}$  (in our case this a bad approximation).

If  $d \gg w$  the inductance is independent of  $x$  and can be determined by numerical calculation, and when  $d \simeq w$  the behavior will smoothly change from the linear increase predicted for small  $d$  to the constant determined for infinite  $d$ . It should be noted that both the approximations in this chapter are subject to small corrections, since in our case  $\frac{d}{w} \simeq 0.05$  and  $\frac{w}{r_1} \simeq 0.1$ .

To use the coil as a pickup device for movement of the resonant mass a magnetic field has to be present as was explained above. The field is generated by trapping a current in the superconducting coil in such a way that it runs 'forever' (a persistent current), to trap this current a circuit is needed as shown in figure 5, with:

$$R = \frac{R_s R_i}{R_s + R_i} \text{ and } V' = \frac{R_s V}{R_s + R_i} \quad (11)$$

The resistance  $R_s$  (switch-resistance) is time dependant and is the essential part of this circuit. The resistance functions as a switch, when it has zero resistance (the entire circuit is superconducting) the current through the coil will stay constant and when it has nonzero resistance (part of the circuit is no longer superconducting) the current through the coil *can* change. The resistance can be manipulated by giving pulses to the nearby heater, when you give such a pulse it warms up (part of) the coil. If a suitable puls is given the shortcut can be warmed up to above the superconducting-threshold while the coil is kept under this threshold, this gives us the possibility to switch between zero resistance and non-zero resistance. Consider a model for the switch in which  $R_s$  is zero except for a period  $\Delta t$  in which it takes the value  $R_0$ . Before  $t = t_0$  there is a current running through the shortcut of magnitude  $I_s = \frac{V}{R_i}$  and no current through the coil. When a heatpuls is given ( $R_s = 0 \rightarrow R_s = R_0$ ) there is a voltage over the coil which leads to a change of the current running through it:

$$V'(t = t_0) = V_c + IR \text{ and } V_c = L \frac{dI}{dt} \quad (12)$$

$$V' = L \frac{dI}{dt} + IR \quad (13)$$

with  $V_c$  the voltage over the coil. Solving this for  $I(t_0) = 0$  gives:

$$I(t) = I_0(1 - e^{-\frac{t-t_0}{\tau}}) \quad (14)$$

with  $I_0 = \frac{V'}{R} = \frac{V}{R_i}$ ,  $\tau = \frac{L}{R} = L \frac{R_0+R_i}{R_0R_i}$ . This means the current through the coil keeps increasing until all current runs through the coil or until  $R_s$  switches to 0. In the later case the current through the coil keeps running because  $\frac{dI}{dt} = \frac{V_c}{L} = 0$ . If another pulse is given while this current is still trapped the change in current can be found by solving equation 13 with  $I(t_0) = I_{trapped}$ .

$$I(t) = I_0(1 - e^{-\frac{t-t_0}{\tau}}) + I_{trapped}e^{-\frac{t-t_0}{\tau}} \quad (15)$$

This shows that by giving a certain amount of current, this current can be trapped entirely as long as enough pulses are given.

## IV. THE FIRST WORKING COIL

### A. Design and fabrication

The basic elements of all the coils created so far are the same:

- coil
- shortcut (a ‘loop’ to shortcut the coil)
- heater (to act as a switch when combined with the shortcut)

To prevent difficult lithographic procedures and low quality joints a counterwound coil has to be used. All coils created by us up to the first working coil have this counterwinding implemented by taking broken circles and connecting them together. The first coil-designs had a thin-niobium line which had to act as a heater. When you give a pulse to this line it should become resistive and warm up the surrounding film. If the pulse is of the right shape/size the shortcut should warmup to above  $T_c$  and become resistive, and current will be trapped as explained in the previous section.

The niobium heater was replaced by a ‘gap’ in the design on which an Al thin-film was deposited which acts as our heater, the resistance of this thin-film was  $62\Omega$  on the first working design (a smaller resistance was intended, but, because of a problem with depositing the Al, the resistance was too high). On the first working design a ‘current-switch’ was added to test an alternative method for trapping current. The current-switch consists of two added connections to the shortcut to force extra current through a part of it, when this current together with the set-current reaches the critical value of the film this part of the shortcut will become resistive and function as a switch. The design of our first working coil is shown in appendix A, and this coil has been successfully tested (chapter IV C).

The coils we used were all made locally with help from several departments/institutes. A Si-disc of 3.9cm diameter was used[5] on which a thin-Nb layer (approx. 300 nm) was deposited using sputtering techniques [7]. In the thin-film the pattern of the coil was created in a developer and the rest of the niobium was removed with an iongun[7]. The process to make a coil can take a long time and it is very important for the quality of the coil that every step is done with great care. After the coil was completed wires were soldered to the pads with an indium-woods mixture and using a variety of techniques. None of the contacts created lasted longer than 2 runs, probably due to bad adhesion of the solder to the (oxidised) Nb film. This problem was solved in the first working coil which had a thin-Cu layer on top and a reliable contact was made by scratching the copper, melting a small amount of indium onto the contacts and soldering the wires onto this using woods solder.

### B. experimental set-up

The setup used for the experiments is a simple insert (appendix B) which can be put directly into a  $^4\text{He}$  transport vessel. There is a calibrated thermometer inside and a hall-probe to measure magnetic field. The insert has a small IVC on the bottom in which the coil is mounted onto a small electrical connection-plate (during testing the IVC was never sealed so there was always helium gas or liquid inside). When testing the coil the hall-probe was placed on top of the coil except when a Nb-disc was used to simulate the superconducting surface of the ‘4-arms’ resonator to measure the effects on the inductance. The disc was fixed onto the coil with a rigid spring-system and was separated from it with a thin kapton-film.

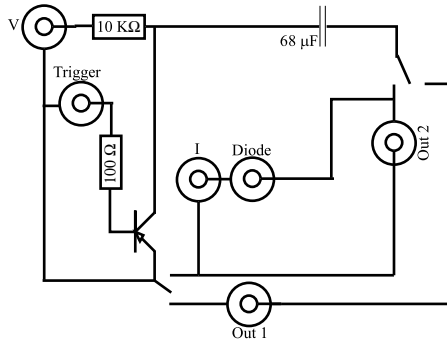


FIG. 6: The circuit used to give a puls to the heater

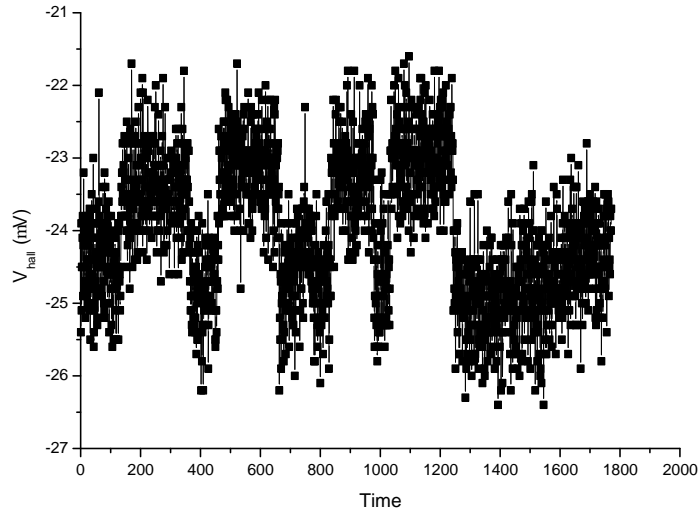


FIG. 7: Trapping of current as seen with hall-probe

The heatswitch on the coil requires a short current-puls for it to function as a switch. Our standard puls-generators were not able to deliver the required power therefore a simple capacitive circuit was made to accommodate this [8](figure 6). The circuit can give a DC-current with a puls added to this or the DC-current and the puls on different connectors. This circuit is used both for the heat-switch and the current-switch.

### C. results and characteristics

In order to check whether the created coils can trap a persistent current we used the hall-probe in the insert to detect changes in the magnetic field while we tried to trap a current. The hall-probe was placed on top of the coil, but because no rigid clamping system was available for the hallprobe, any measurements we make cannot be translated into the precise amount of current trapped, only relative changes can be measured during a run. After a lot of trial and error in both coil-design and heat-pulses we were able to measure a change in the magnetic field due to the trapping of current, and it was possible to reproduce and control the measurements (figure 7). The pulses we used had a minimal size of 22V and a maximum of 40V, and had a minimum length of  $2.5\mu\text{s}$ . Because the pulses were created with the simple capacitive circuit described before the pulses were (roughly)triangular-shaped. The current-switch was also tested and found to be working but it was more convenient to test the remaining properties of the coil using the heat-switch. The minimum pulses needed for the current-switch were 30V and  $3\mu\text{s}$ . The dependance of trapped current with current set was measured with the hall-probe, this led to the result in figure 8. In this figure we see a

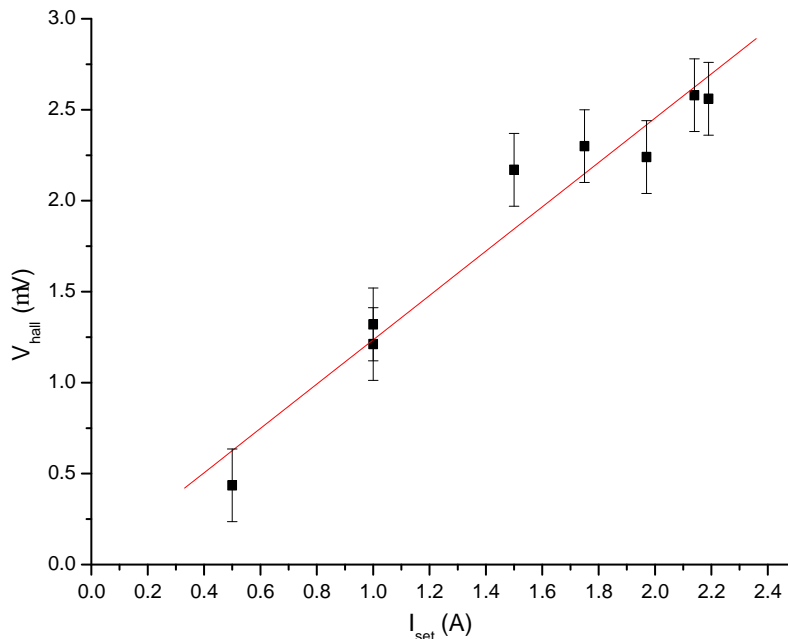


FIG. 8: A linear dependance was found between the current set and the measured hall-voltage

linear dependance of the trapped current to the magnetic field which is what we expected from the theory explained in the previous chapter. The hall-probe was also used to test the decay of the persistent current. Current was trapped and then left for more than 20 hours while the hall-probe measured the magnetic field approximately once per 5 minutes. The data was then fitted with  $I = I_0 e^{(-t/\tau)}$ . Measurements show  $\tau = 50.1$  days, this value will be larger in the final setup inside miniGRAIL because the coil will be shielded, the environment less noisy and the temperature is  $\pm 20$ mk instead of the 4.2K at which we tested.

To test the quality of the thin-film Nb we measured the critical current at different temperatures (figure 10) and the  $T_c$  (figure 11). The tests suggest a  $\tilde{I}$  of  $4.07 \pm 0.04$  at 50 mK, however an article by Wedenig *et al.* [6] shows that the relation between the current and temperature should be

$$\frac{I_c(T)}{I_c(0)} = 1 - \left(\frac{T}{T_c}\right)^2 \quad (16)$$

and often sees a deviation at higher T, in our case this would translate to  $\tilde{I}(T=0) = 2.96 \pm 0.07$  when we use the measured  $T_c = 8.69 \pm 0.05$ K.

A finite element analysis of the inductance has been performed for the model case by *Javier Sesé* (TU-twente), the result of this analysis is shown in figure 12.

The inductance was measured by trapping an amount of current in the coil and while doing this monitoring the voltage across the coil with a fast oscilloscope triggered by the heater-puls. On the scope a measurement is performed of the area of the shortcut-voltage ( $V_c$ ). This area can be translated into the inductance using the integral version of  $V_c = L \frac{dI}{dt}$ .

$$LI_c = \int V_c dt \quad (17)$$

A typical measurement can be seen in figure 13. The noise right after a puls is given is caused by the heater-puls and is probably due to pickup between wires, this noise has a small area which has to be taken into account when processing the measurements. The measured inductance without a superconductive surface near the coil is  $583 \pm 3$  nH

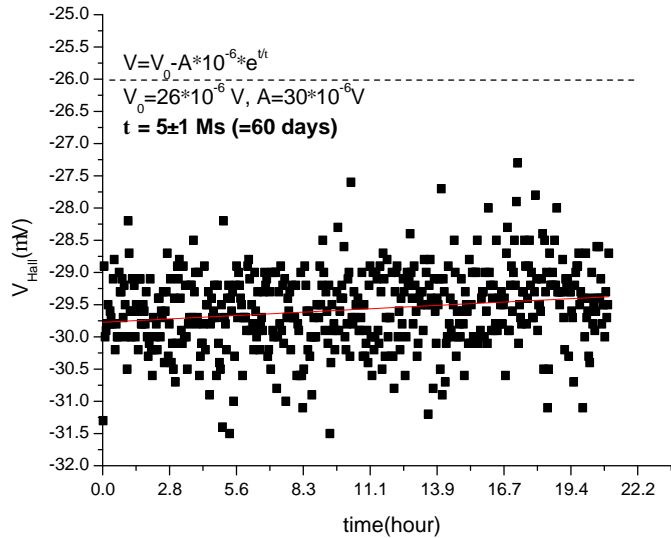


FIG. 9: The decay of persistent current

(figure 14) which is consistent with the numerical calculation. To check the dependance of our measurement method on current and temperature the inductance was measured at different temperatures and with different currents. The graph (figure 14) shows no dependance between  $L$ ,  $I$  and  $T$ . During these measurements we observed that we couldn't trap any additional current after a critical value was reached, even though  $\int V_c dt$  was clearly nonzero. Trying to trap currents higher than the  $I_c$  of the niobium still caused all current to be removed because of the loss of the superconductivity in the coil. This behavior was further studied by measuring this critical current  $\tilde{I}$  at different temperatures (figure 15). An explanation for this can be that there is a weak spot in the coil which becomes resistive when enough current is given. The amount of current needed depends on temperature in the same way  $I_c$  depends on temperature. This means we see an increasing  $\tilde{I}$  when  $T$  decreases. A resistance in the coil of magnitude  $R_c$  would give rise to a maximum trapped current of  $I_c = \frac{R_s I}{R_c + R_s}$ . This behavior was not seen during the first measurements and increased after it was first seen. These measurements suggest a loss of quality of our coil in time, probably due to oxidation of the Cu-layer on top of the coil or damages. Tests with the hall-probe were consistent with this theory (fig 16).

To test the behavior of the coil in interaction with a superconducting surface near it we used a 5mm thick Nb-disc which was clamped on top of the coil using a spring system. Between the coil and the disc kapton films were used to isolate the coil from the disc and to create the separation we wanted. Using the method described above we measured the inductance as a function of the thickness of kapton. We expect a linear behavior when the thickness  $d$  is small. When  $d$  becomes large the inductance asymptotically approaches the inductance without the disc, in the region where  $d$  is neither small nor big a smooth change from linear to asymptotic behavior is expected. The measurements (figure 17) show a difference with theory, when  $d$  is small the inductance is about twice the predicted values, but at large  $d$  the values are equal. The difference between theory and experiment is possibly caused by the roughness and poor flatness of the used surfaces. Because a kapton film is used to create the gap roughnesses on the surface and dust particles can make the actual gap much bigger than the intended gap, this would show in the measurements as a non-constant offset of  $L(d)$  giving bigger values of  $L$ . The graph only has 3 measurements because the coil was no longer able to trap current due to damages of the film.

## V. SECOND WORKING COIL

### A. design, fabrication and setup

The coil design was adapted after our experiences with the first coil; the small turns in the coil were eliminated by using a double spiral as coil instead of connected circles, the heater was placed as far away from the coil as possible

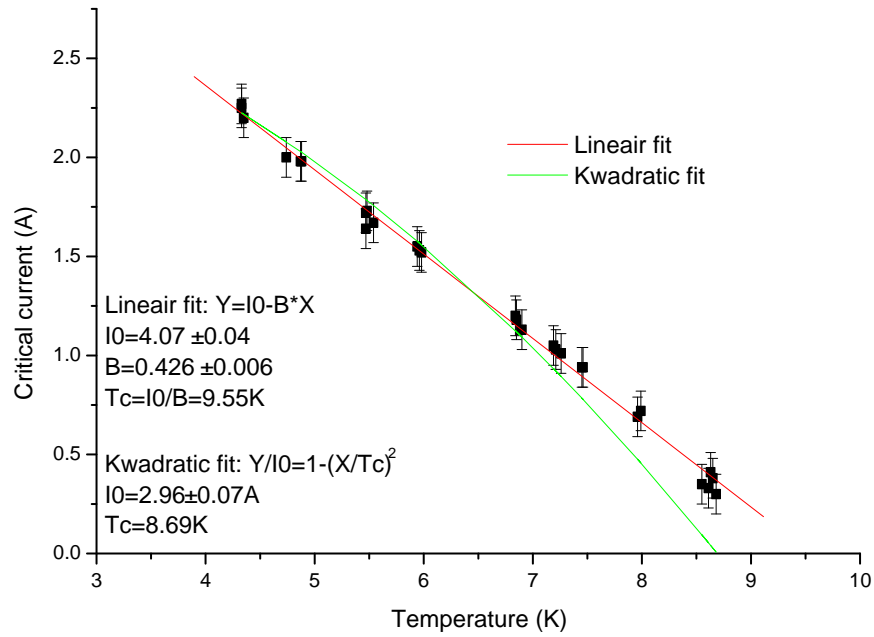


FIG. 10: Critical current at different temperatures

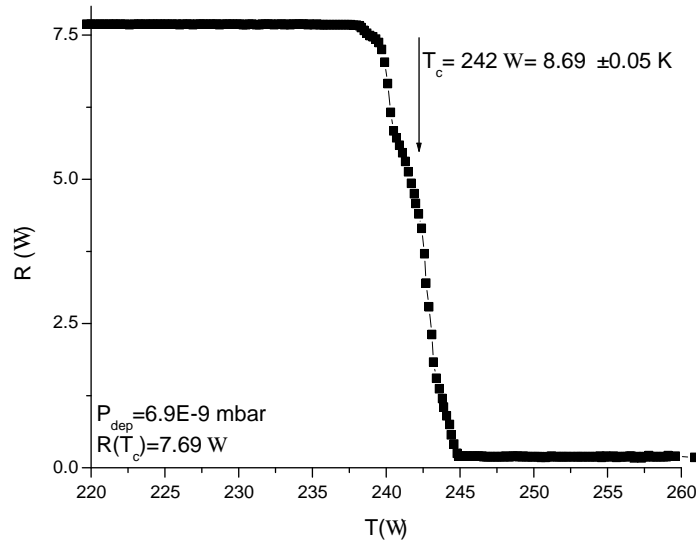


FIG. 11: The resistance of the shortcut shows a clear critical temperature

and was smaller ( $23\Omega$  poladium), the connecting lines of the heater and critical current switch were placed next to each other to prevent pick-up between the wires and the size of the coil was increased (figure 18). The coil was made on a si-disc with a diameter of 2 inch and a film of  $400 \pm 5$  nm niobium +5nm aluminium. The coil was made at TUtwente, using a liftoff lithography technique. Because the coil is bigger than the previous one the coil doesn't fit in the IVC of the insert. The IVC was replaced by a  $\mu$ metal cylinder and the whole insert was fitted onto a flange which fits on a dewar (the cylinder is too big to fit in the  $^4\text{He}$  transport-vessels).

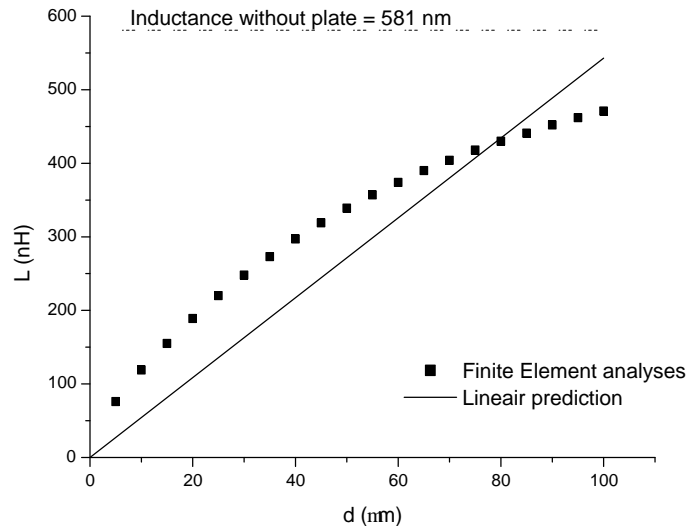


FIG. 12: Results of finite-elements analyses

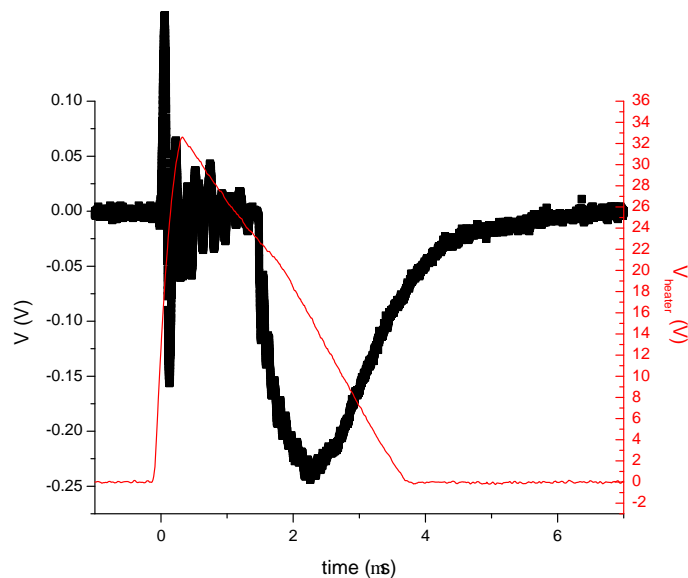


FIG. 13: Example of one of the measurements

## B. results

Both the heat-switch and the current-switch of the new coil were found to be working, but the current switch doesn't always trap current when it is expected to, therefore all tests were made using the heat-switch. The inductance was measured as described in the previous chapter,  $L=529 \pm 2$  nH (figure 19). The quality of the film was tested by measuring the  $T_c$  (figure 20). The  $T_c$  of bulk niobium is 9.25K and of the film it is  $9.4 \pm 0.2$ K. The critical current of the shortcut is 6.2A, however we are only able to trap 4.0A. The difference in trapped and critical current is probably caused by a lower  $T_c$  of the coil. Another possibility for a lower maximum current is the heat generated by both heater and shortcut with current running through it. If the combined power of the two heat sources is big enough to warm up the rest of the coil slightly the maximum trapped current will be lowered.

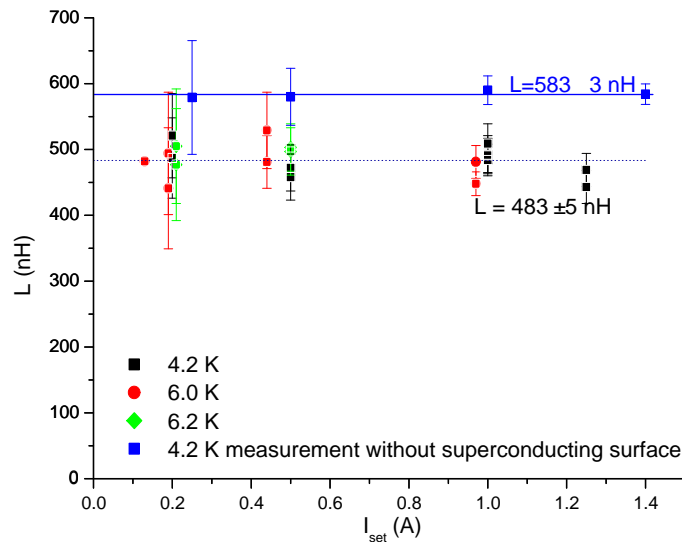


FIG. 14: Inductance measurement with different temperatures and currents

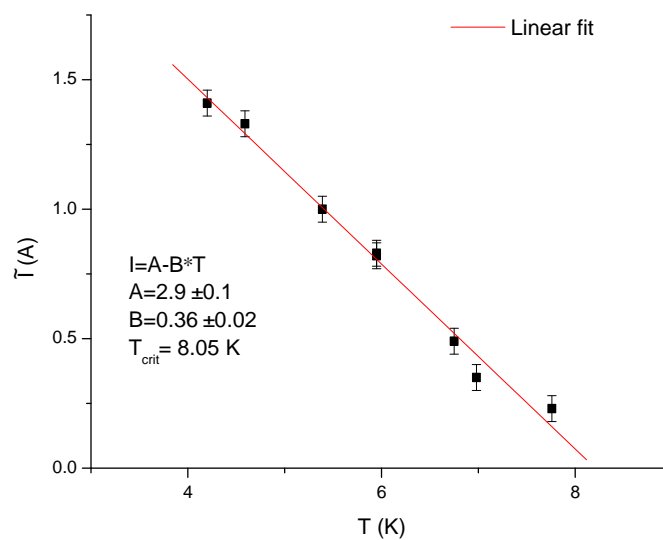


FIG. 15: Maximum current trapped

## VI. FUTURE DEVELOPMENT

To improve the design of our last coil the resistance of the shortcut will be decreased by using a wider line. Also a design has been made to test a thin-film transformer. The transformer is to be made as a tri-layer system, but this has not yet been successfully created, the design is shown in figure 21.

The final transducer will need a system to create a gap between the second resonator and the coil. We proposed a way of achieving this which utilizes the difference in thermal contraction between CuAl6 and Al5056. When cooling the transducer the gap between the Al5056 and the resonator should become approximately  $10 \mu\text{m}$ . The test-setup is

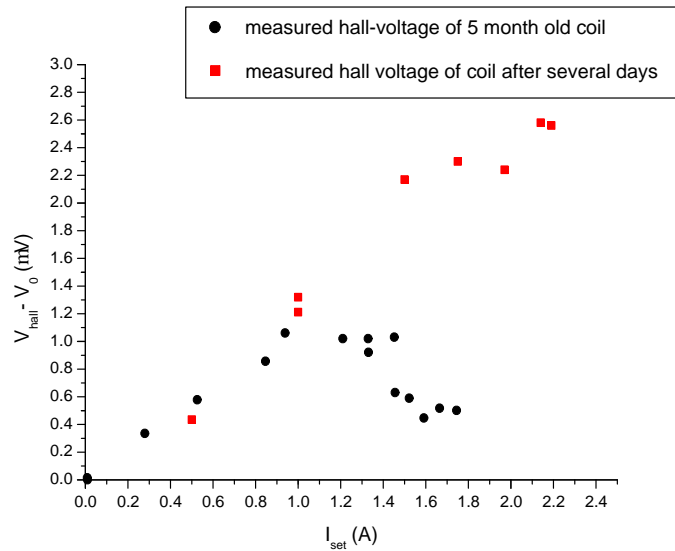


FIG. 16: The properties of the coil change with its age

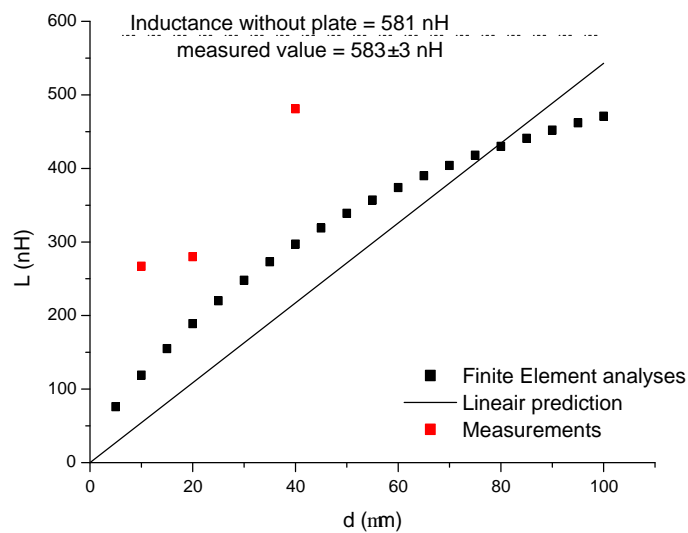
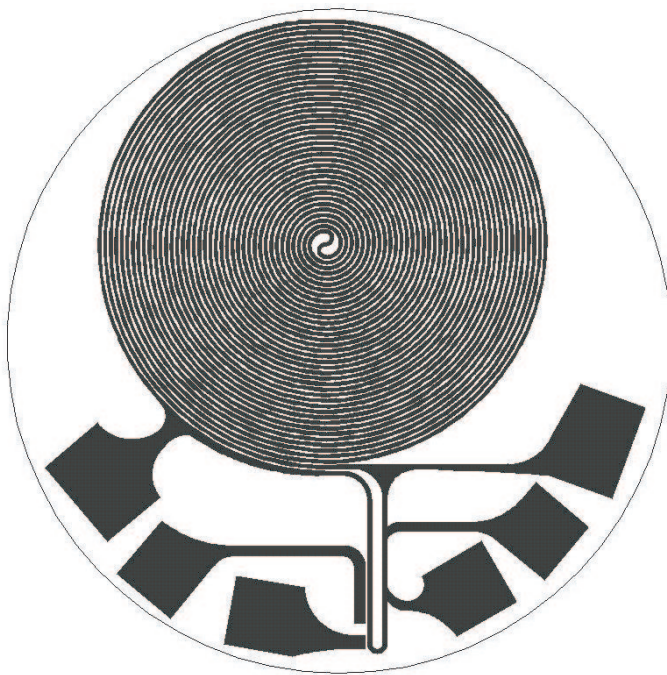


FIG. 17: LvsD

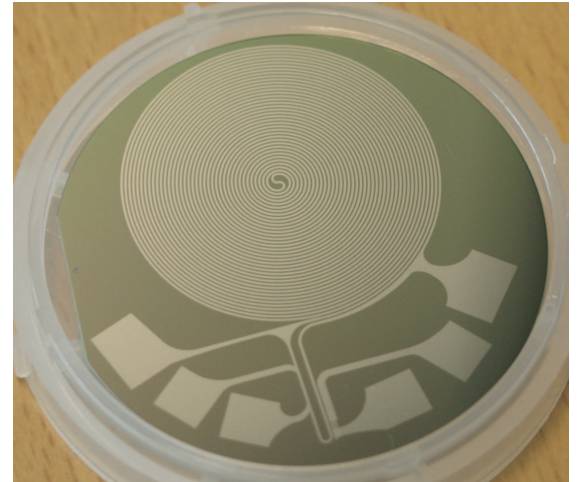
made by gluing a Si-disc, which has a thin-gold film on top, on a CuAl-disc. This is cooled with liquid nitrogen and placed on top of the Al-resonator and after letting it warm up it can be cooled to LN2 to create the gap. Measuring the capacitance  $C$  between the gold and the aluminum with surface area  $A$  gives the average distance  $d$  between the two.

$$d = \frac{A\epsilon_0}{C} \quad (18)$$

We haven't been successful in testing the gap because of problems with gluing the si-disc. After cooling, the glue is not able to hold the si-disc in place which makes testing impossible.



10 mm  
Design of the coil



Picture of the finished coil before soldering the wires

FIG. 18: Design of the second working coil

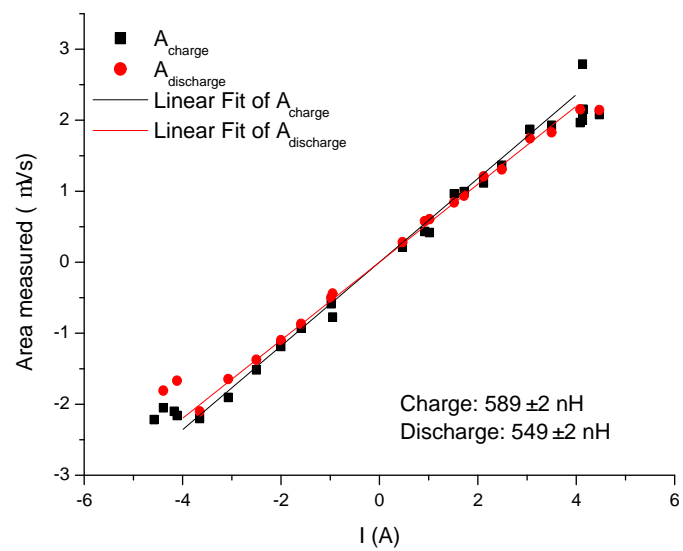


FIG. 19: Measurement of the Inductance

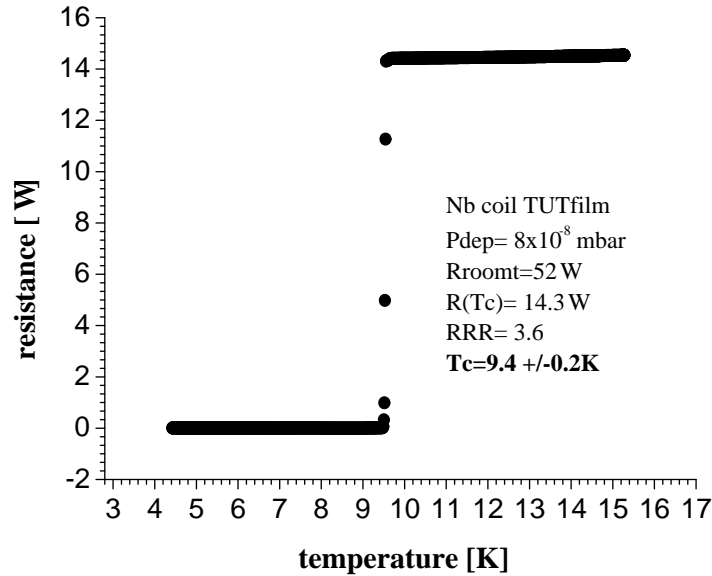


FIG. 20: The resistance of the shortcut at different temperatures

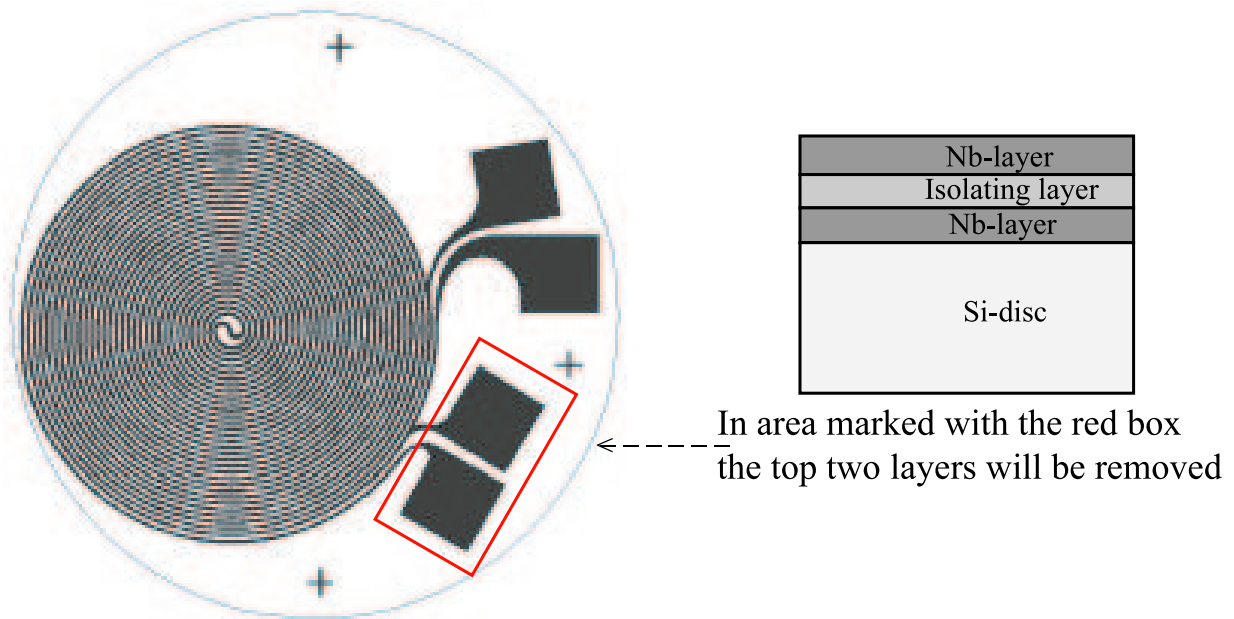
## VII. CONCLUSION

We were able to design, construct and successfully operate a thin-film Niobium coil which had a critical current of 2.2 A and a  $T_c$  of  $8.69 \pm 0.05K$ . This coil worked for over 5 months. These results led to a new coil with even better characteristics. The maximum trapped current of the 2nd coil was 4.0 A and a  $T_c$  which is the same as bulk niobium (9.25K). The measurements on these two coils and the theory of their workings should make designing/constructing the final coil for miniGRAIL easy once the desired values of the inductance are known. Also we can conclude that the two possible coupling circuits to the dc-squid give a comparable signal and the choice between the two circuits can be made based on construction simplicity.

## Acknowledgments

I wish to acknowledge the support of the whole QV3 group and L. Gottardi in particular. Also I would like to thank Vincent Kooij for the useful discussions about superconducting electronics and J. de Haan, R. Bosch for a helping hand when needed.

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- [1] [www.minigrail.nl](http://www.minigrail.nl) for general info or for detailed information CQG 19(2002) 1943-1948, L Gottardi *et al.*
  - [2] Currently being developed at TU-Twente
  - [3] A more detailed report on the miniGRAIL mechanical resonators was made as an iEN report, *TRANSDUCER DEVELOPMENT for miniGRAIL*. Unpublished, July 2001.
  - [4] More on different transducer systems can be found in 'The detection of Gravitational waves' D. Blair, Cambridge University Press (1991)
  - [5] Made by the LIS
  - [6] Superconducting NbN microstrip detectors - NIM 433 (1999) 646-663
  - [7] With help of Marcel Hesselberth of the metals-group
  - [8] Made/designed with help from Hibbe van der Mark.



### Design of a thin-film transformer

FIG. 21: Designs for tests of a thin-film transformer

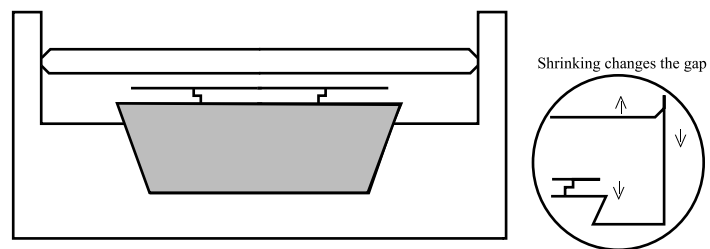
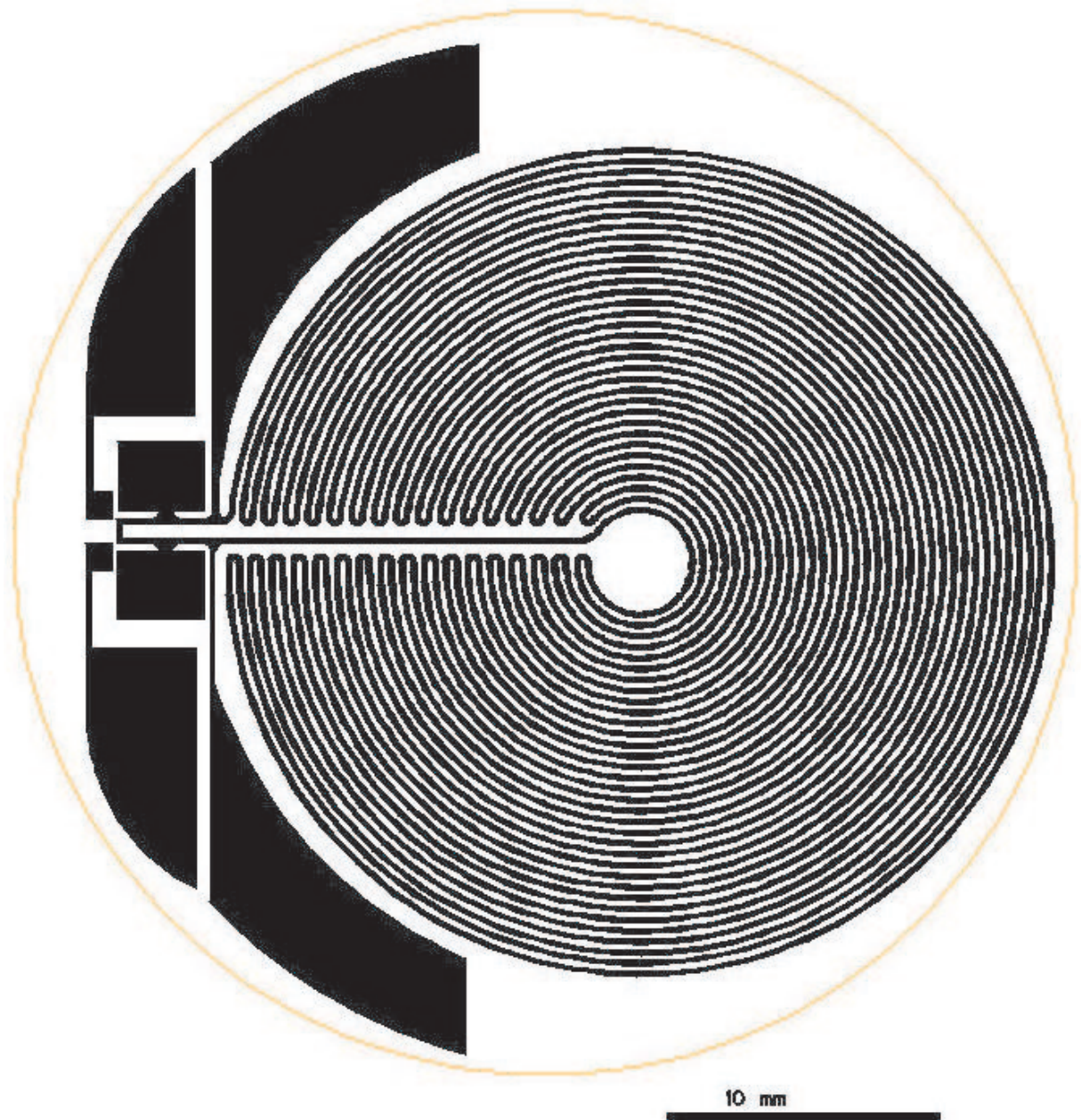


FIG. 22: Gap setup

APPENDIX A: DESIGN OF THE COIL USED DURING THE EXPERIENTS



APPENDIX B: INSERT  $^4\text{He}$ 