REPORT ON SUMMER INTERNSHIP AT ICMP/LQM

Constructing a Susceptometer Made of Two Hall Probes

SARAH DEBLER

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Introduction

In order to determine if a material will become a superconductor at low temperatures, one can either measure if the resistance goes to zero, or one can make use of the Meissner effect: a superconductor will expel any external magnetic field from its inside, thus increasing the magnetic field above its surface. This second idea shall now be used to construct a device for measuring the magnetic field at low temperatures in a small pressure cell. It will consist of Hall probes in different configurations. The advantages of this type of measurement are mainly that it is a non-contact measurement: no wires have to be attached to the actual probe. Moreover the Hall probes and all necessary connections can be soldered and will thus be much more stable than former techniques which mostly include connections which oxidate rapidly. I compare possible configurations to build the susceptometer and perform first measurements with lead samples. The final measurements should be done in a pressure cell to find out if that setup will be applicable in those conditions.

Methods

Material

There are 5 different types of Hall probes (all produced by Chenyang Technologies), which vary in size, material, signal strength and in the range of applicability. Probes 3 and 4 are made of the same material, just as 2 and 5, so they show a similar behaviour. Probes 1 and 2 are comparably big, probes 3 and 4 the smallest, probe 5 is in between.

Number	Material	Product Name	Hall Voltage [mV], 0T	Hall Voltage [mV], approx 0.1T (max value)	Ratio signal/zero
1	AlGaAs/InGaAs/GaAs-2DEG	CY P15A	2	21	10
2	InSb	CYSH 12 AF	0.012	0.4	33
3	GaAs	CYS J 166A	0.001	0.006	6
4	GaAs	CYSJ 106 C	0.002	0.005	2.5
5	InSb	CYTY 108 A	0.002	0.004	2

Table 1: product names, properties and signals of the used Hall probes (see measurement 1a)

First measurements with a single probe in a DC field show that among the big probes, type 2 has the highest signal, whereas among small probes, 3 has the strongest signal. In the following measurements, further criteria as to which probe has to be used will be found, giving as a result that probe 3 has the best properties.

Types of measurements

We distinguish in principle two setups: in the first, there is a constant external field, a DC Hall current supply and the Hall voltage is measured by a DC multimeter. The second setup uses in addition to the constant external field a small AC magnetic field generated by coils which are run by a lock-in amplifier. The amplifier is also used to lock in to the Hall voltage, which will oscillate with the frequency of the coil current. Thus a more precise measurement is achieved yet for small signals this is sometimes difficult to measure as the signal gets quite noisy. In the DC setup the Hall voltage that is measured is proportional to the magnetisation of the material. The magnetisation describes the field that an external magnetic field induces in a material. In case of a superconductor, the induced field will have the opposite direction of the external field, thus the net field in the inside will cancel out. When doing an AC measurement, which measures a derivative of the Hall voltage, it is proportional to the derivative of the magnetisation, that is to say the susceptibility χ. The susceptibility describes how well an external magnetic field can penetrate a material. As we know, a superconductor behaves as a perfect diamagnet and has thus susceptibility $\chi = -1$. When doing measurements with the lock-in amplifier, the value of interest is Y: the reference is given by the oscillating field of the coils, which is caused by a current. The Hall voltage, that is to say the signal, has a 90 degree phase shift relative to the current and will be displayed as the Y value.

Experimental devices

The measurements are performed at room temperature and at 4 Kelvin in the Kelvinox evaporation refrigerator to cool the samples down to temperatures where they will become superconducting. At room temperature the external magnetic field is provided by small cylindrical magnets (with a field of approx. 0.1T) and a big cylindrical magnet (B = 0.4T). These magnetic fields are not very homogenous and the setup can move relative to the magnets. At 4K the setup is completely fixed and the external magnetic field is provided by a very long coil, thus those measurements are more precise. In both cases the coils used for the AC field are the same. Their magnetic field is very small and cannot be measured with a Gaussmeter.

The Hall probes are put onto a conductor board and connections are created by soldering copper wires to the small metallic feet. The magnetic coils for the AC measurements are put around the probes and also attached. The copper wires are fixed to a connector which makes the link to the measuring electronics. The conductor board is mounted on a copper stick, which can be screwed to the copper part which can be seen in figure 2, right at the bottom.

Later some of the measurements are done in a pressure cell, where the probes will be placed inside a Teflon cup which is set in oil as a pressure medium. Pressures up to 20kbar can be applied. Again, the setup will be cooled down to low temperatures.

Figure 2: Kelvinox Dilution Fridge (source: http://www.oxinst.com/products/low-temperature/dilution-refrigerators/kelvinoxmx/Pages/kelvinoxmx.aspx)

Principle idea for the setup of Hall probes to obtain a susceptometer

The idea for the measurements is to set up two Hall probes in row so that the Hall potential difference and thus the signal will effectively cancel out if both probes are submitted to the same magnetic field. If a sample is put on one of the probes, there will be a non-zero signal which can be measured with a very high resolution and where the influence of noise and unwanted background will be smaller.

The original setup of those two Hall probes was to wire the probes up in row and to measure the Hall voltage and the current along different diagonals in each probe.

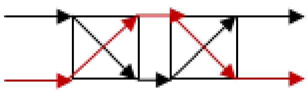


Figure 3: first possible setup of two Hall probes to get zero signal

The current flows along the black arrows; the voltage is measured along the red ones. It turns out that with this setup the potential differences do not cancel out and we never get zero signal (see measurements 8a, 10a). This is mostly due to the fact that the way the current flows cannot be controlled – a part of the current will flow along the voltage bridge between the probes (green arrow) and will be measured as a voltage there.

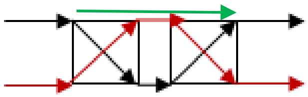


Figure 4: problem with setup of figure 3: current flows along voltage bridge

This contribution from the current to the Hall voltage signal is expected to be approximately constant, so when doing the AC measurement we expect that the signal will correspond more or less to the Hall voltage. Still even there the signal is not zero (see measurement 4a). So another setup has to be used.

The idea is to make the current (black lines) flow in parallel along separate paths so it cannot contribute to the Hall voltage we measure.

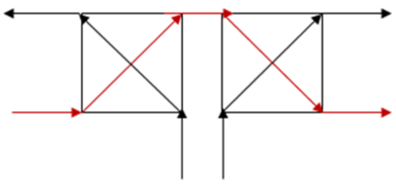


Figure 5: possible solution: two Hall probes using parallel currents

When one Hall probe was cut open it could be seen that it is probably not symmetric under rotation by 180 degrees, that is to say it makes a difference along which diagonal current and voltage are measured. In the first setup of double probes, the current was measured along the diagonal which was used for the voltage measurement in the subsequent probe. We expect that the cancellation of signal will work better if the voltage is always measured along the same diagonal. A convention will be fixed that the current enters the probe at the upper left corner (probes are marked with engraved letters and numbers on top of them). The wires for entering the current and respectively the wires where the current flows out can be joined together.

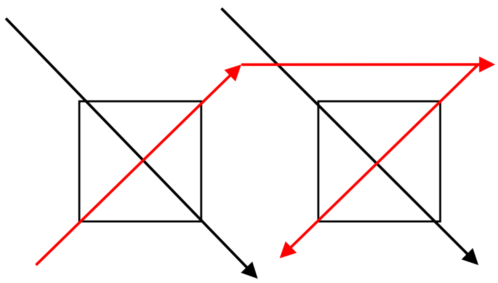


Figure 6: optimized setup of double Hall probes with parallel current and symmetric diagonals

Two modifications to this setup are tested: including two 1 kΩ resistances at the current entries (figure 7), and the other one with an additional 2 kΩ resistance at the voltage bridge (figure 8)

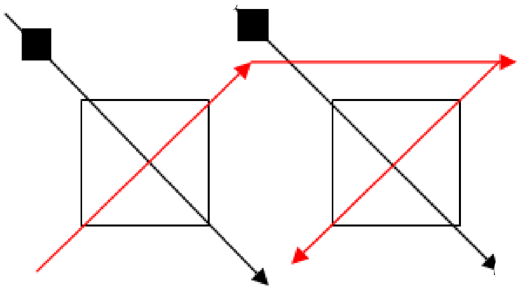


Figure 7: double setup, parallel currents, 2 resistances

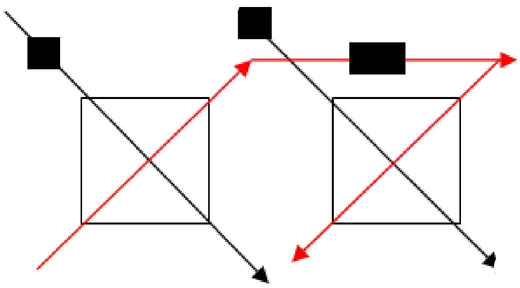


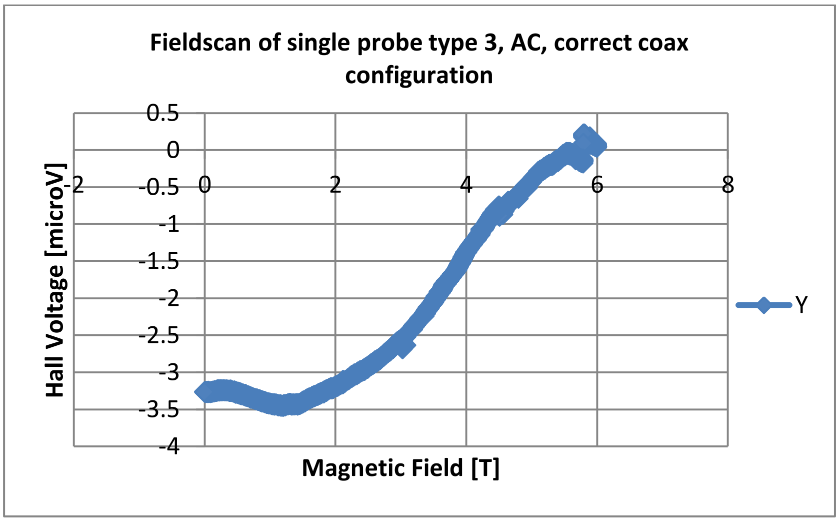
Figure 8: double setup, parallel currents, 3 resistances

All those tests were done on probes of type 3 as they seem to have the best properties at low temperatures (see section**:** First measurements of single and double probes (setup figure 2) at 4K).

Results

First measurements of single and double probes (setup figure 2) at 4K

The first two rounds of measurements were done with single probes and the first setup of double probes (figure 3), where the current flows through the probes in row. The problem with those measurements is that only one coax cable was used to enter the Hall voltage signal into the amplifier – but the amplifier does not work in this configuration, the signal has to be brought into the device in the core of two separate coax cables, using the A-B mode in the signal channel. This was done in the third round of measurement. I did a check-up measurement to compare if the influence of the wrong coax configuration on the data was considerable, and it showed that there are such big differences that probably all the AC measurements done with only one coax are useless. In the overview list over all performed measurements, those are noted in grey, and the data is not used in this final report.



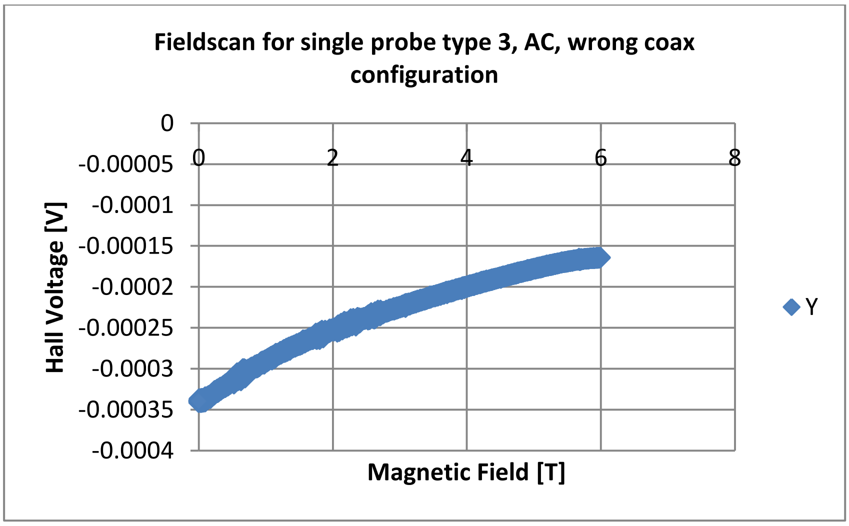


Figure 9: comparison of background for probe 3, single, with the two different coax configurations, scanning from 0T to 6T, at 4K

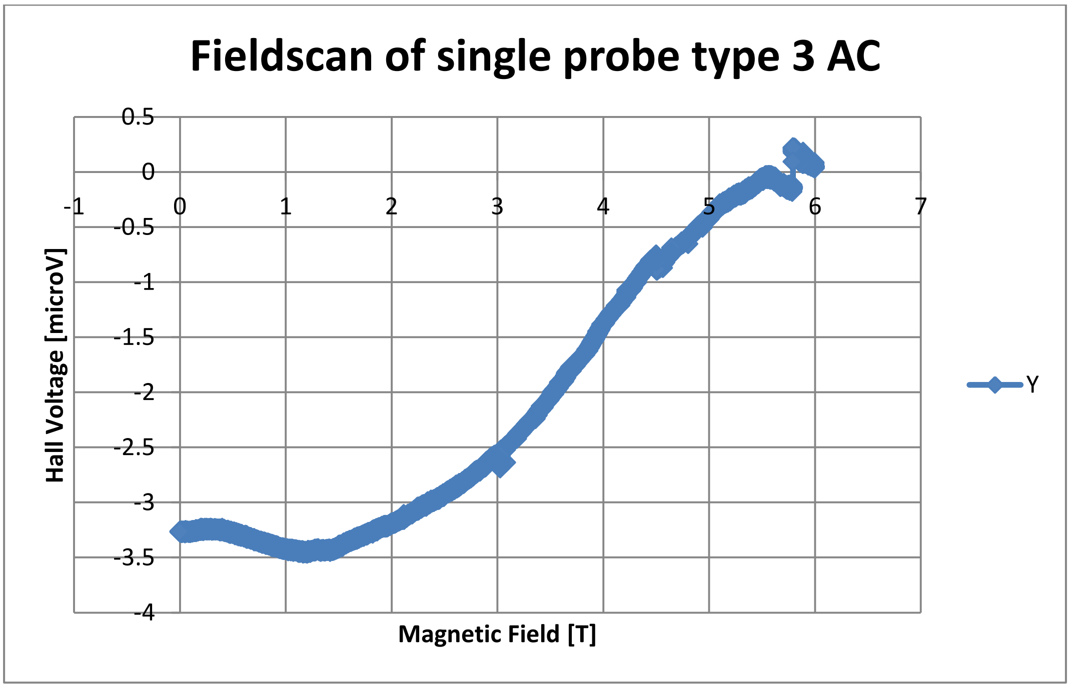
The behaviour we would in principle expect from the probes is:

- In a DC measurement of the Hall voltage while increasing the external magnetic field, we expect UHall to grow linearly with B.
- When increasing the Hall current and measuring the Hall voltage, it should give a linear increase plus saturation at a point which should correspond to the maximal input current given in the product information.
- Increasing the AC current to the coils will also give a higher Hall voltage signal with a linear dependence. It can also be assumed that locking in to the signal will be easier.
- An increase in the DC Hall current while measuring in an AC magnetic field should not influence the Hall voltage much, as the Hall effect saturates when a certain current is reached. Carrier density might depend on the DC Hall current, but we expect the effect to be relatively small.
- The background measurement (slowly increasing the magnetic field while applying an AC field and measuring the lock-in voltage) should give a constant slope. Anything that is approximately linear should be fine.
- Changing the oscillation frequency of the AC coils to higher frequencies should reduce the influence of inductances. See next paragraph for why it seems strange

The conclusions that can still be drawn from the measurements with wrong coax configuration are:

1. In all DC measurements (see measurements 17, 17.1, 8a, 10), the behaviour we expect can be seen. What can also be noticed is that the double configurations give a higher signal than the single configurations and that linearity with increased external magnetic field is a weak point with most double probes. Improving the setup as I discussed above will help.
2. In the measurements (12a, 19) that were done with the wrong coax configuration, one point can be clearly seen: if the oscillation frequency is increased, Hall X stays more or less constant, whereas Hall Y drops continuously. As Hall Y is the value which corresponds to the Hall voltage we want to measure, this seems to indicate that measurements cannot be performed at too high frequencies, although of course the measurement would have to be repeated with the right coax configuration to be sure that the effect will be the same there.
3. In a very extensive measurement(13, 19a, 40) the background is tested: a data point is measured around twice a second for 5 hours while the external field is slowly increased or decreased from 0 to 6 Tesla at a rate of 0.02T per minute. The additional AC-field produced by the coils allows a precise lock-in measurement of the Hall voltage. This was done for the double setup of probes (type 2, 4) and for single probes (type 2, 3, 4). The data can be used for a precise comparison of the different types and setups of probes. It will also serve as a background measurement: from this we know how the Hall voltage behaves when reacting to a growing external field and we can then compare it to future data from probes including a sample. Again unfortunately most of those measurements were done with the wrong lock-in settings and without using symmetric diagonals. Yet one correct measurement of a single probe of type 3 was performed (measurement 40). The signal grows with the magnetic field, as we expected, but it is not linear. There is a possible explanation for the non-monotonic behaviour at the interval 0T to 2T. What is done is not a field scan but actually a time scan while the magnetic field is expected to decrease constantly from 6 to 0T, and thus the time scan would correspond to a field

scan. Yet it is possible that the field decreased too fast and thus the last part of the data could describe a constant field (as 0T has already been reached). As we expect the probe to warm up a bit, this could explain the increase in the Hall voltage.



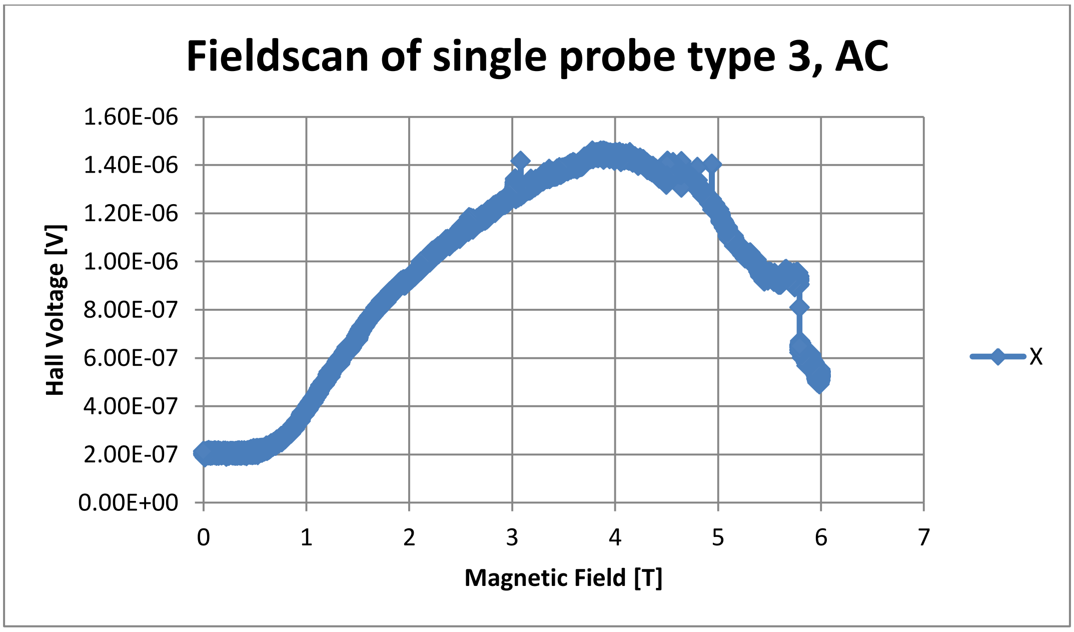


Figure 10: scan of Hall voltage in AC measurement while external magnetic field was decreased from 6T to 0T, X and Y Hall at 4K

The values that are displayed in the X display correspond to the imaginary part of the Hall voltage. It does not seem as if a lot of information could be extracted from it.

To answer the question which type of Hall probe is suited best for the measurements, the data of the single Hall probes at low temperature is used (see measurement 17 to 19a).

Criteria for a good probe are:

- Linear response of the Hall voltage to increase of the magnetic field in DC (fulfilled for 1, 3, 4) and to Hall current with saturation at high current.
- Large Hall voltage of single probe when measured in AC coils (but zero for the double setup)
- Flat field dependence
- Flat temperature dependence

For all the criteria involving AC measurements, I do not have any reliable data. The temperature dependence of type 3 probes in the optimized double setup with the two coax cables is small compared to a single probe of type 3 (see measurement 40a), which shows that some unwanted background effects cancel out in the double setup. Also the DC Hall voltage response to an external magnetic field is very close to linear with type 3, while giving a reasonably large signal (see measurements 10a, 17). For measurements in the pressure cell it will also be helpful that probe 3 has the smallest dimensions. From the data I have, it seems that probes of type 3 are best. All further measurements with this probe work more or less, yet it would be interesting to see if other probes might give even better results. Another pattern with optimized probes of all 5 types has been set up, but no measurements have been done on it yet.

Measurements at room temperature of optimized double setup of Hall probes (type 3)

The measurements at room temperature (see measurement 30a, 31a, 35a, 36a) indicate that the best possible setup is the one shown in figure 6: it has least noise and the closest to zero signal (it is not exactly zero, but quite close). Notice that measurements at room temperature, especially AC measurements, are quite difficult as the signal fluctuates a lot. I therefore noted the minimal and maximal value for each step and averaged them. Also the signal to a small probe (a little screw) of the possibly best configuration was not very high, so another comparison of the setups was done at low temperatures (see section: Measurements at 4K of optimized setup of double probes (type 3))

Measurements at 4K of optimized setup of double probes (type 3)

The last optimized pattern that was tested at 4K includes only probes of type 3. Two single probes are set up, on top of one of them I glued a sample (which is a 2mm*1mm*1mm piece of lead). Configuration 3 is the one shown in figure 3: the current flows through the probes in row, and a sample is glued on the second probe. Configuration 4 is the one that works best: it is shown in figure 6, and there’s a sample on the second probe, too. Configuration 5 is depicted in figure 7, is has two additional resistances and a sample on the second probe.

The effect of the sample should be the following: lead has a critical magnetic field Hc of 80.3mT (at 0K) and respectively a critical temperature of 7.19 K. If this field or this temperature is passed, the superconducting state is destroyed and the magnetic field, which was before expelled from the volume of the lead, can now enter it. Thus the magnetic field at the surface (where the Hall probes are put) will go down to a lower value and the Hall voltage will decrease with it.

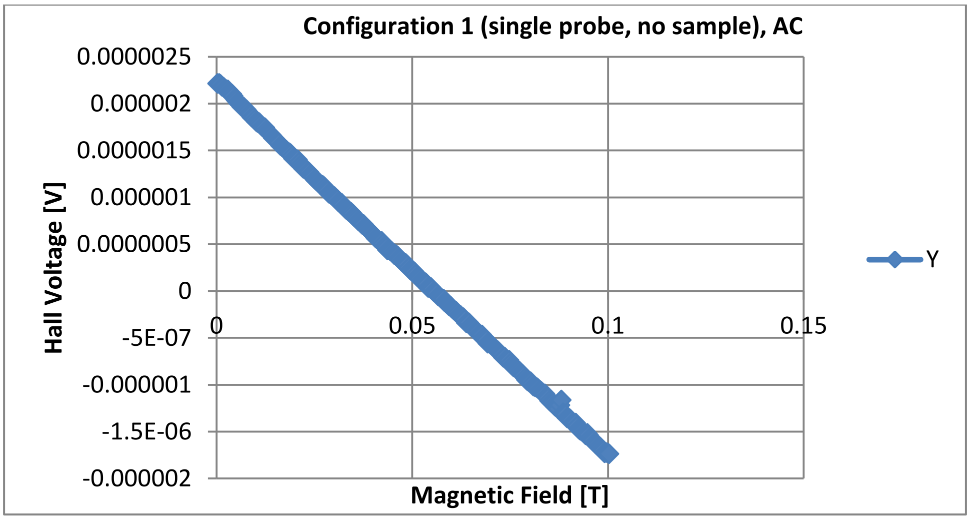
To see if this actually happens, I do scans of both temperature at constant magnetic field and of external magnetic field at constant temperature. Notice that the phase transition is not expected to occur precisely at the values noted above: as we are set at a finite temperature, the critical magnetic field will be lower.

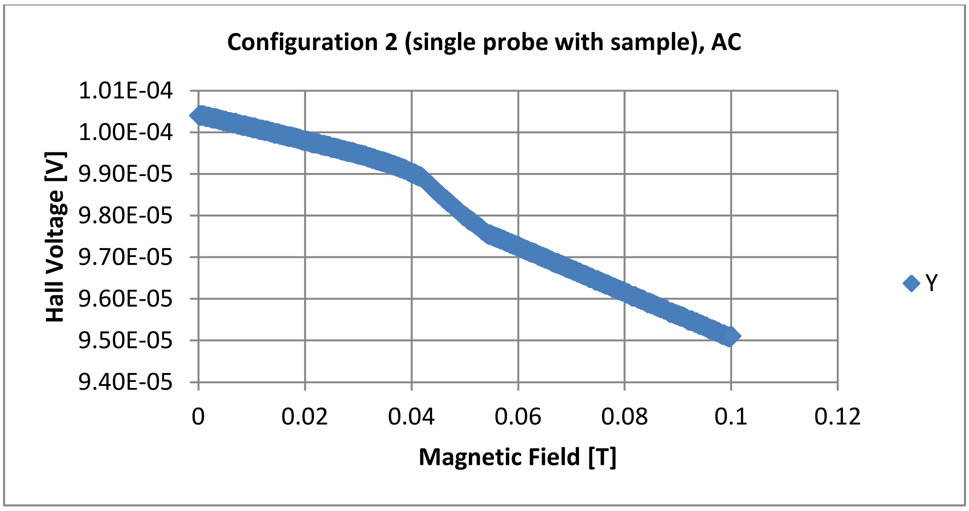
Field scans across the critical field at 4K for 5 different configurations

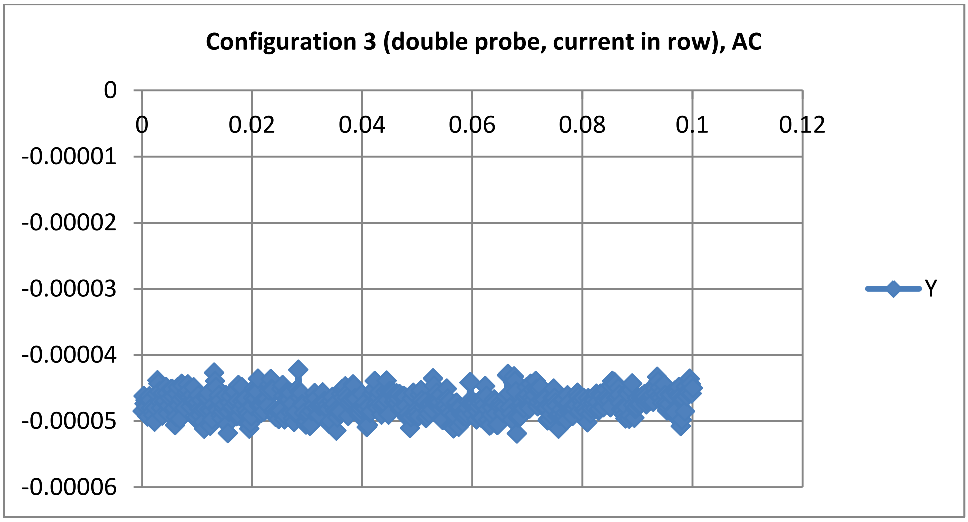
A first measurement series was done scanning from a magnetic field of 0T to 0.1T and thus passing over the critical magnetic field (see measurement 40.1).

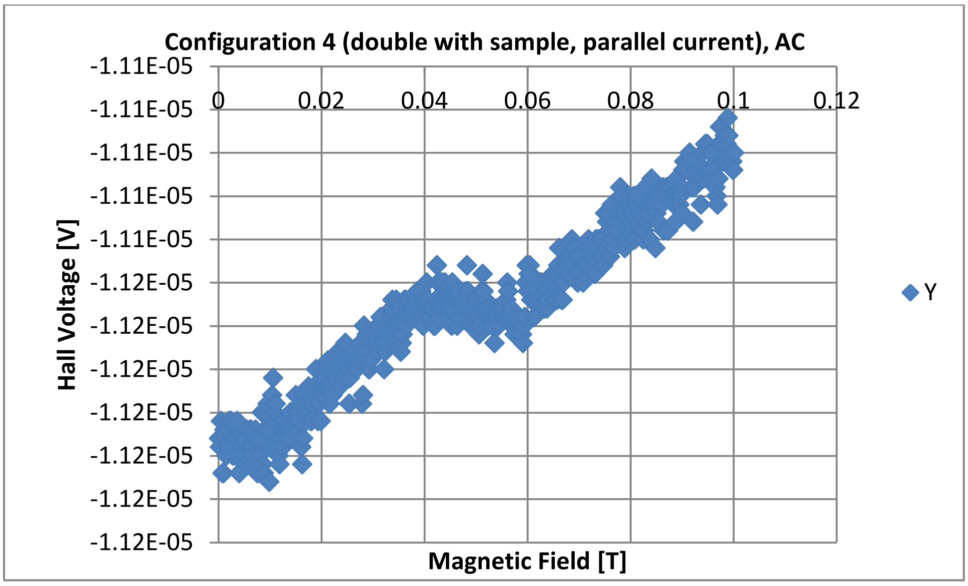
Note that whenever there is a negative slope, that is to say the Hall Voltage decreases with the magnetic field, this is simply because the voltage cables were plugged in the wrong way around. Multiplication with a factor -1 will give what we expect: linear growth of the Hall voltage with the external magnetic field

Apart from configuration 3 and 5 where nothing can be seen except noise, we see what was expected in the AC measurements: for a single sample without probe, there is no jump in the susceptibility. It is a bit surprising that the susceptibility is not a constant, but this could be explained by magneto resistance: the resistance of a material grows with an externally applied magnetic field and thus the voltage grows, too. An offset positive slope is therefore to be expected. If a sample is put on top of the probe, the susceptibility suddenly jumps. This shows that when superconductivity is destroyed by the critical field the external field can suddenly penetrate the lead sample. Configuration 4 shows the same behaviour, except that the signal is by a factor 10 smaller than with the single probe – thus we generally get the behaviour we expected.









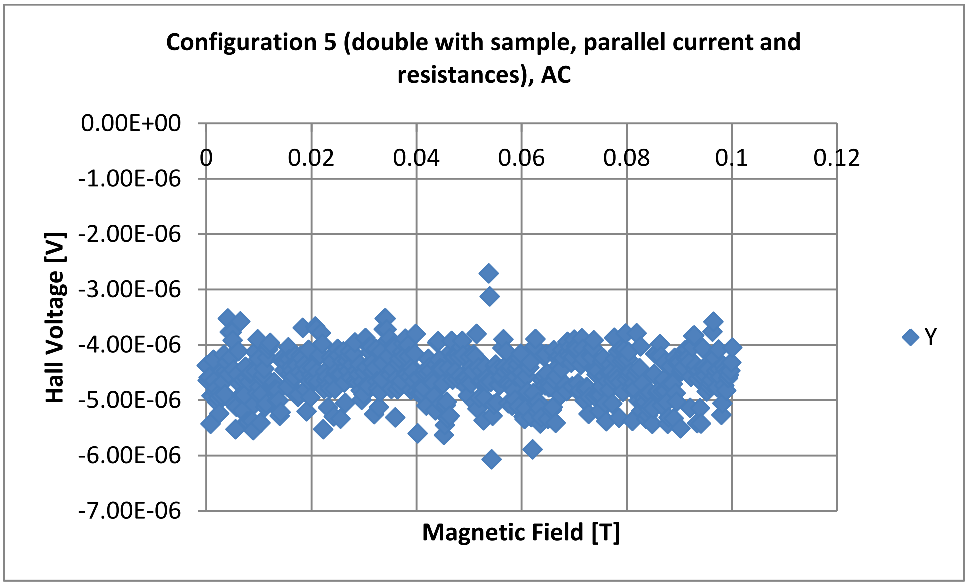
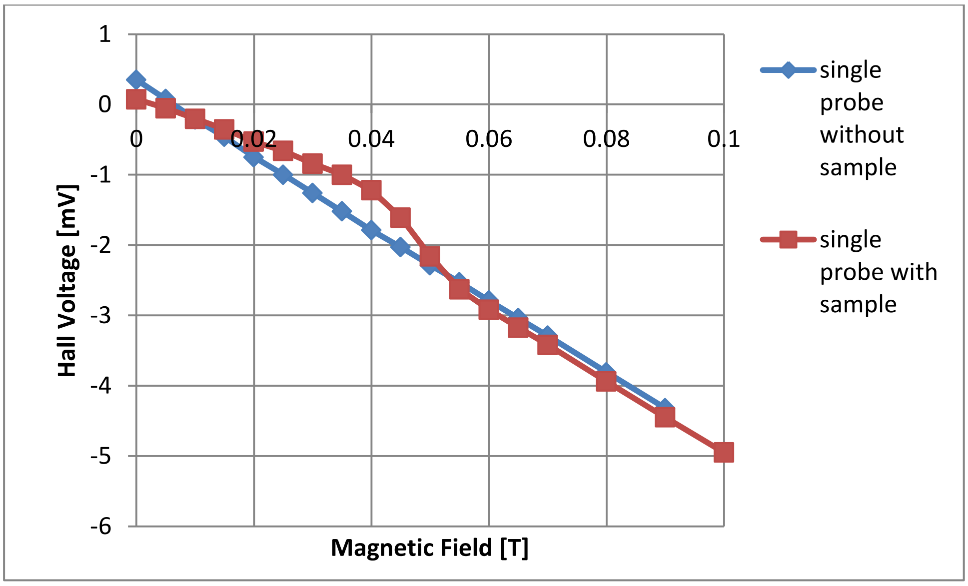


Figure 11: field scans of 5 different configurations of Hall probes (type 3) at 4K (see measurements 39)

It is surprising that the difference between configuration 2 with and without sample should be that big once superconductivity has broken down: I would rather expect them to show the same Hall voltages. It is good that the transitions take place at around the same magnetic field in all cases where a signal could be seen. So up to now the reaction to the sample is qualifiable; it still has to be found out if it can be used to really quantify the changes in magnetisation and susceptibility.

A DC measurement will show how the magnetisation behaves. Notice that in DC measurements the signal is in the order of mV, whereas it is of the order of microV in the AC case.



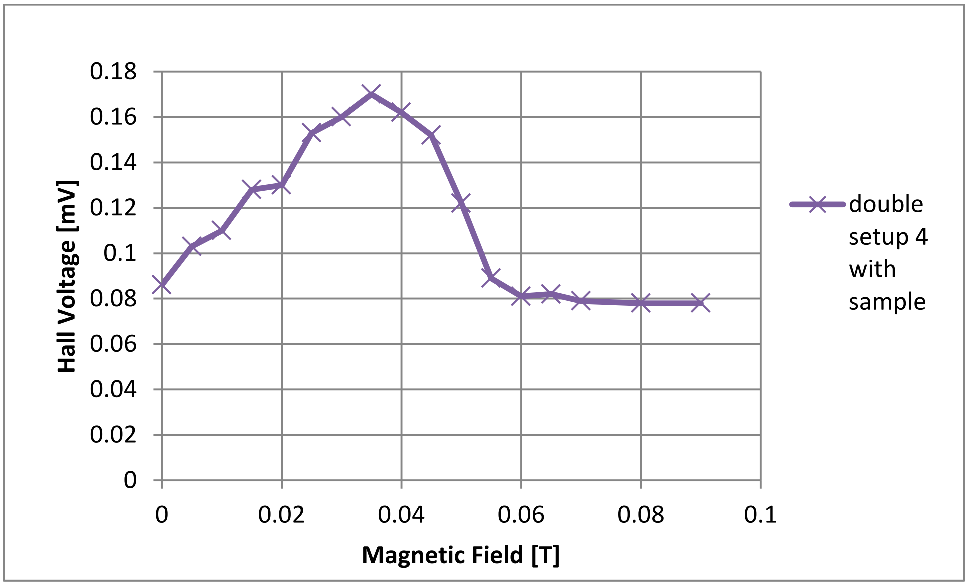
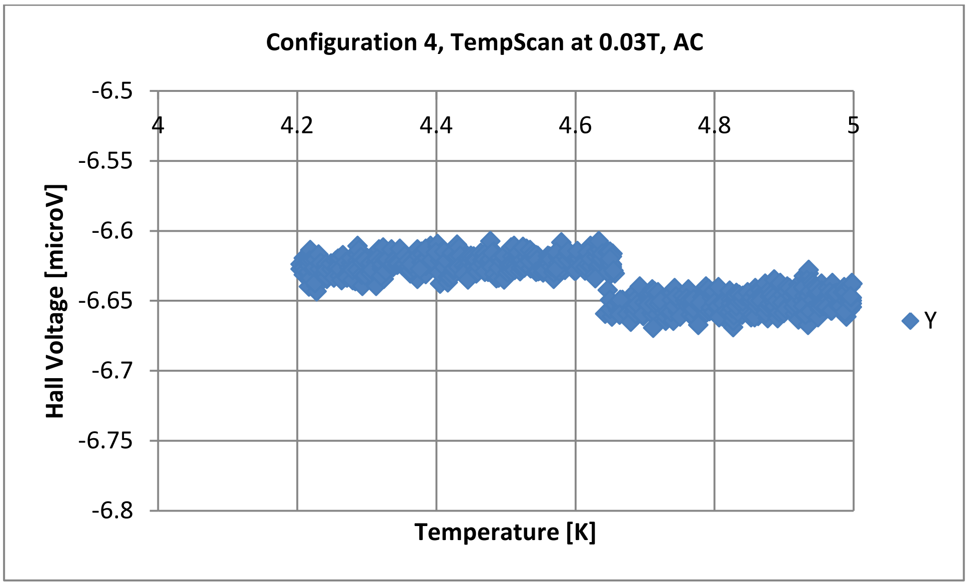


Figure 12: DC Hall response to increased external field around the critical field at 4K (see measurement 40.1)

Again what is measured corresponds quite well to what is expected: for a single probe we see that at a value around 0.04 T there is a kink in the magnetisation which happens when the superconducting state of the lead sample is destroyed. If there is no sample on top of it, the magnetisation is just linear. The double setup gives very good results: it can be seen how the magnetisation increases linearly as long as the sample is superconducting. In this case, lead is a perfect diamagnet and any externally applied magnetic field will induce an internal magnetisation which is directed opposite to the external field. At around 0.4T the superconducting phase is destroyed and the magnetisation jumps back to the original value and stays constantly there. Configurations 3 and 5 were also measured but show no reaction to the sample.

Temperature scans across the critical temperature at constant external magnetic field

Experience shows that the phase transition to superconductivity should be visible even more clearly when doing a temperature scan. The first obtained data for this looked quite promising as a very sharp step in the susceptibility can be seen.



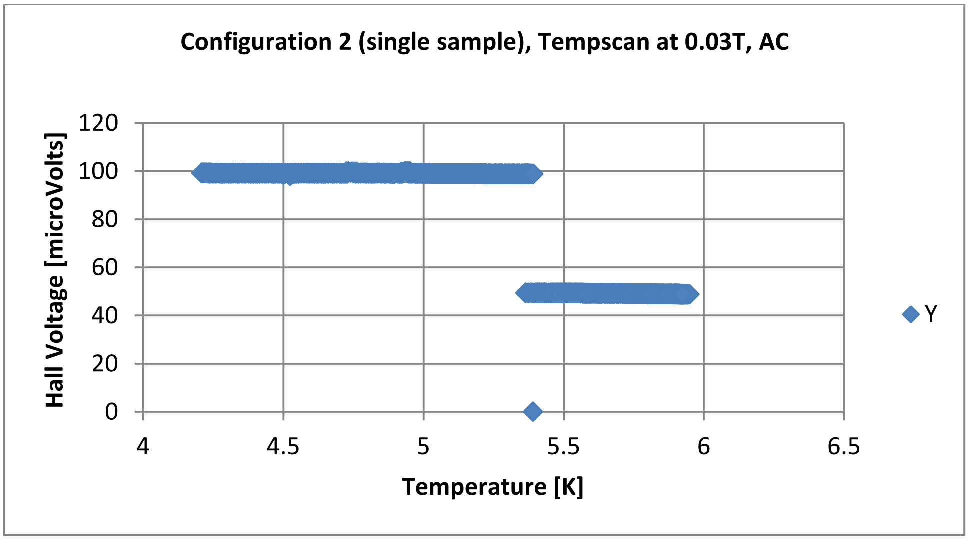
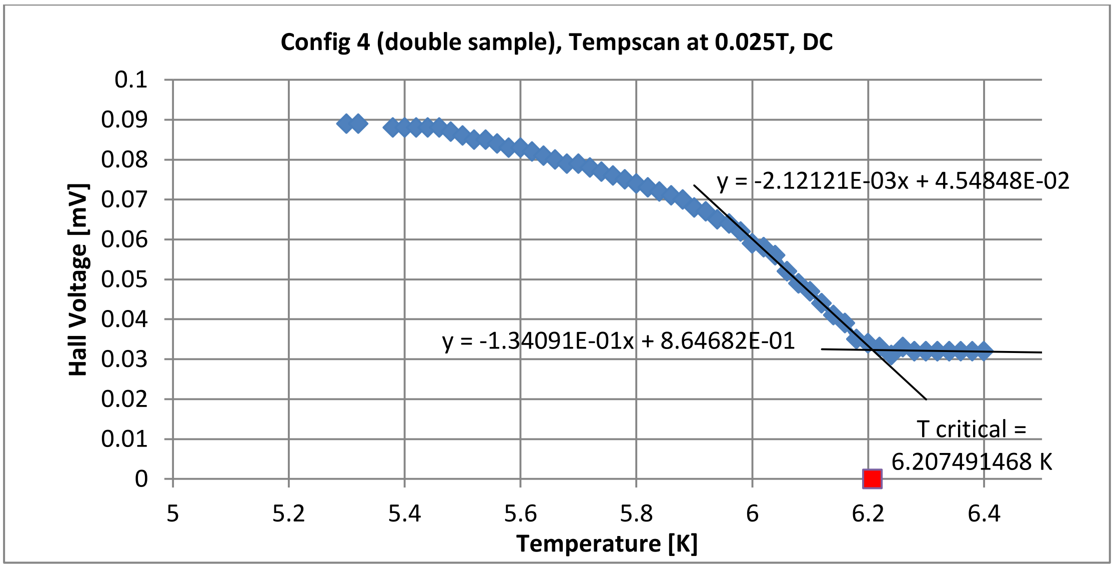


Figure 13: AC Hall voltage response to an increase in temperature at constant external field (see measurement 40a)

Again the data obtained from configurations 3 showed no jump and was very noisy. Configuration 5 was not measured, but a similar behaviour is to be expected. Configuration 1, the single sample, was measured and showed a completely flat line as expected. The poor results of Configurations 3 and 5 might have been due to a broken connection – so the connections were tested and proved to be fine. Thus it is clear that configuration 4 is the best one.

The susceptibility measurement (AC) shows a clear jump that happens at around 4.6 K in the double configuration. Even in the single configuration with the sample, we could see a clear jump. Yet it was surprising that the jumps happened at quite different temperatures. Moreover, I calculated the size of the jump for the temperature scan and compared it with the size of the step in the field scan. They should be of the same order, which is approximately fulfilled for configuration 4 (jump in field scan: 0.0226 microV compared to the temperature scan: 0.0166 microV) but not for configuration 2 (jump in the field scan: 0.801 microV compared to 0.0949 microV in the temperature scan). When trying to reproduce those measurements, it was not possible, so it has to be assumed that the jump was due to an external disturbance. Some DC field scans (see measurement 40.1) were done to determine very precisely at which field the phase transition takes place. Then DC temperature scans at constant external field were done, where the phase transition could be seen very clearly. A measurement was done to see if there is some temperature dependence of the DC Hall voltage, which does not seem to be the case, but the measurement was not very precise or extensive.



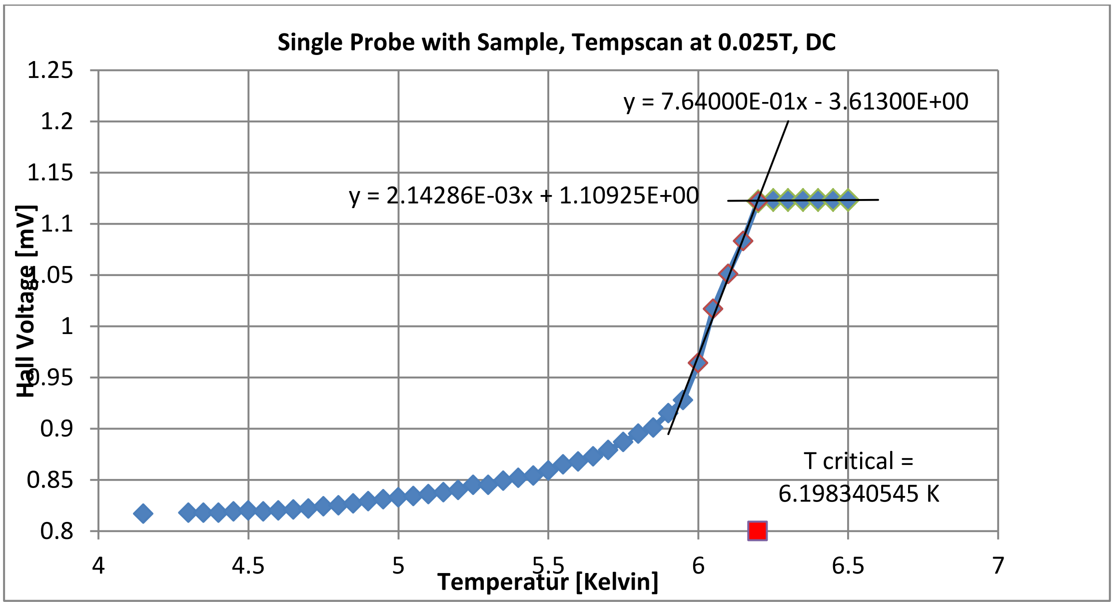
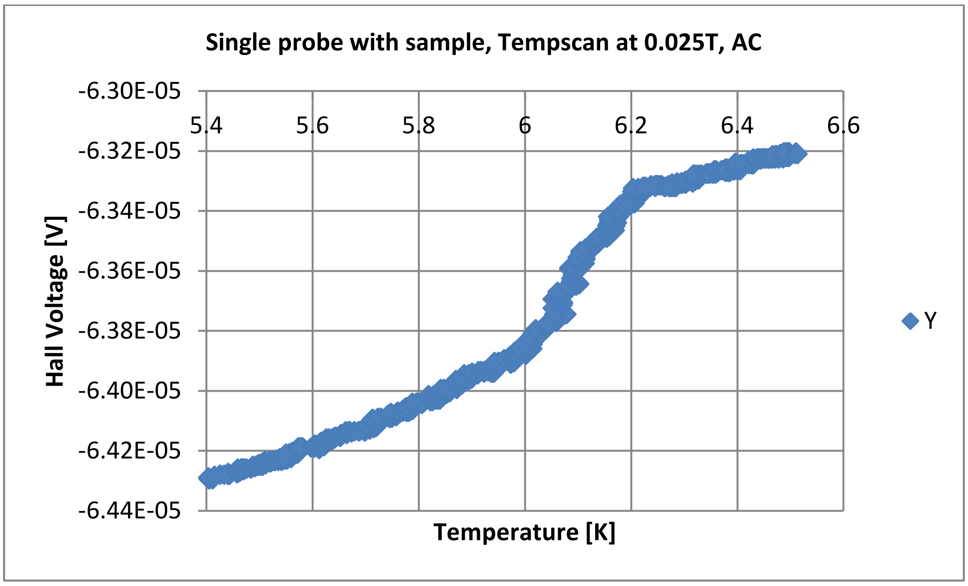


Figure 14: DC Hall response to increase in temperature at constant external magnetic field (see measurement 41a). The difference in the critical temperatures which were calculated by those measurements is 0.00915K.

Yet even in very precise AC temperature scans it was difficult to see a transition. In addition the susceptibilities were not constant any more but showed slopes from time to time. Results of the measurements varied in slopes of the susceptibility and in if there could be seen a step at all. The most precise measurement is done at an oscillation voltage of 0.3V which will make the lock-in easier. In principle it is possible to do an AC and a DC measurement at the same time (which might be an interesting concept, as magnetisation and susceptibility could be measured simultaneously then), yet it is expected that the DC measurement will introduce noise to the AC measurement.



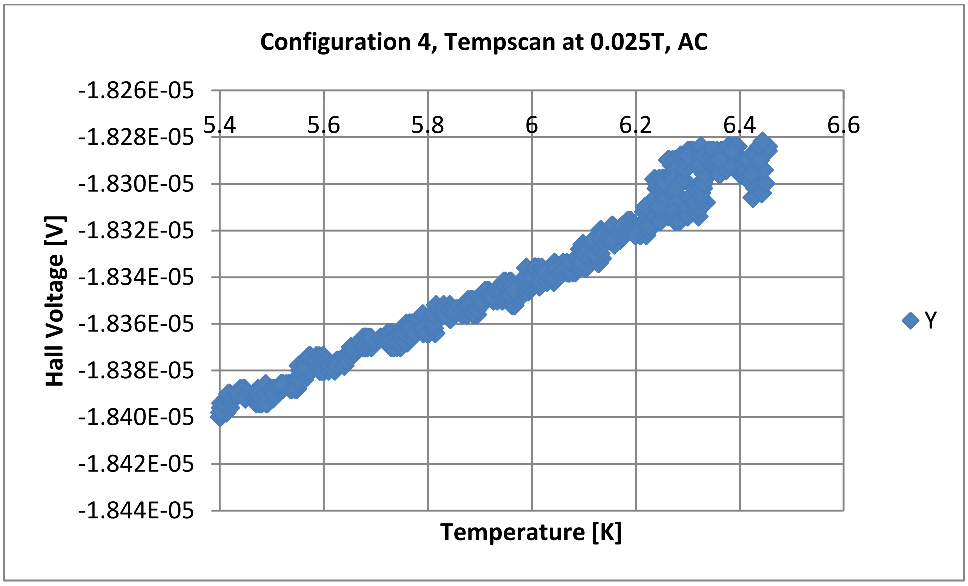


Figure 15: AC Hall response to very precise temperature scan at constant external field and higher oscillation amplitude (see measurement 43)

This poor reproducibility (compare figure 14 with figure 12) leads to the conclusion that DC measurements seem quite more reliable at the moment. The jump in the magnetisations could be seen in all cases. Thus this way of measuring will be used in the future experiments.

Magnetisation measurement in a pressure cell on a sample of lead

The measurements on superconductors are performed in a pressure cell to see how the superconducting phase behaves and in order to control it. The pressure cell has a small inner Teflon cup with a diameter of around 5 mm into which a double setup of probes should be put. For that, two Hall probes of the same type are stacked on top of each other and glued together top to bottom. The connections between the feet are made by bending the lower ones upwards, so they can just be soldered together without using any wires. 4 cables (which in this case are 25 micrometer thick gold wires) are attached to the probes. We obtain a very stable setup with good connections.

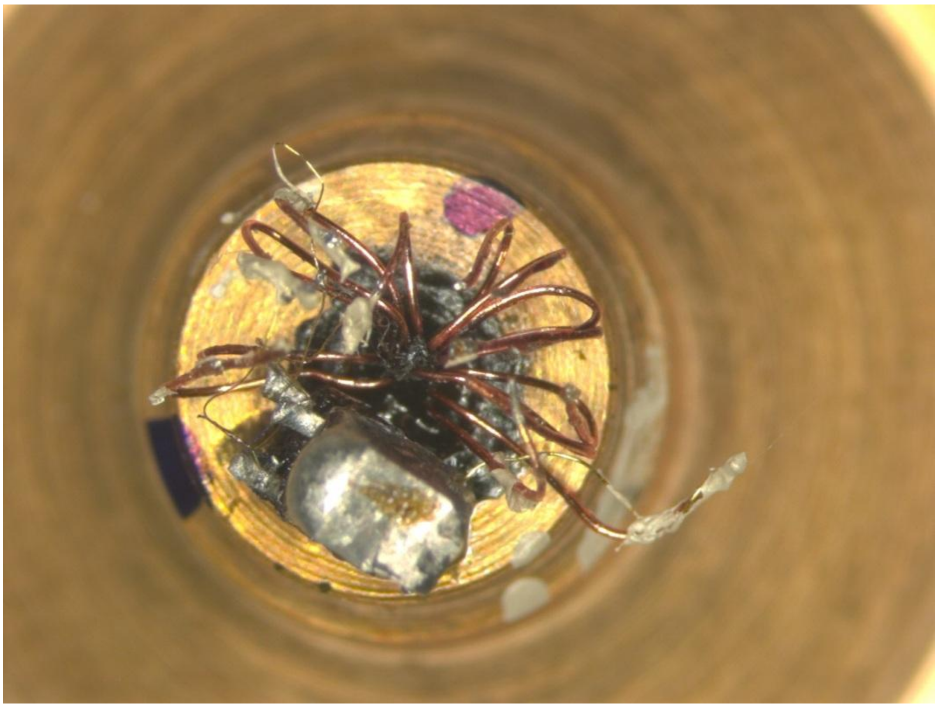
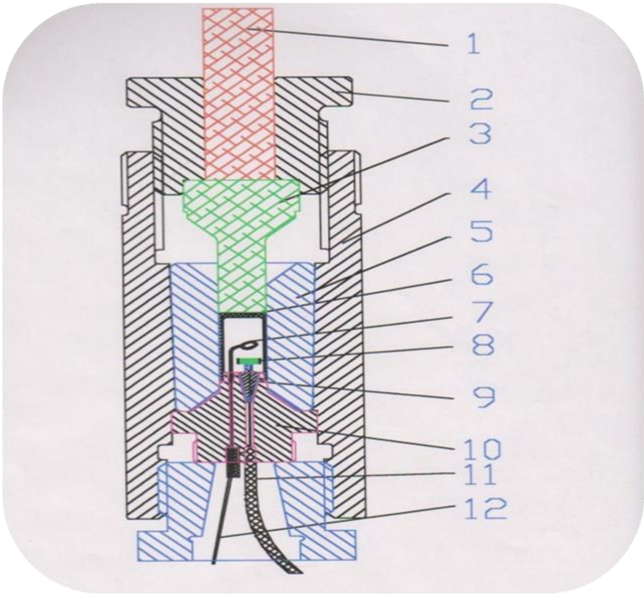


Figure 16: two Hall probes on top of each other and a lead sample as seen from above mounted on the obturator (see 10 in following figure). 3 gold wires (I in, U in, U out) exit the probes on the left side and are attached to copper wires. One can see the two separate exits for the voltage at the upper left corner. All the other connection feet are joined and soldered together. On the right side, only one wire (I out) is needed.



1.Pusher, 2.Screw, 3.Piston, 4. Body, 5. Insert, 6.Teflon,
7. Manganin, 8. Sample, 9, 11. NMR input, 10. Obturator,
12. Electrical leads

Figure 17: Sketch of a pressure cell. The Hall probes and sample are placed at position 8.

The purpose of this measurement is first to see if the Hall probes and the connections will withstand the high pressure in the cell, and second to see if the physics that has been observed so far will change considerably under high pressure. If that is the case, a lot of further measurements would have to be done to qualify the behaviour. Measurements under high pressure have not been performed yet; but the setup for it would be available.

Discussion

The measurements show that the general idea of using two Hall probes to determine if the material is a superconductor at low temperatures works. Modifications to the way the two probes are wired up improve the signal and make it closer to zero in the case when no sample is applied. Exact cancellation of the signal is not achieved. DC measurements of the Hall voltage are proportional to the magnetisation and show a clear phase transition when the critical temperature or the critical field is passed. Susceptibility is measured in AC measurements, in some cases the phase transitions can be seen as well. We see that DC measurements are at the moment more reliable, so what can be measured with this setup is the magnetisation, whereas susceptibility measurements in AC are not well understood and not reproducible.

Further measurements should focus on several points: first of all determining if other types of probes will give better results. The pattern for those experiments is already prepared. Then further measurements on the AC Hall voltage could lead to this being fully understood and thus being able to measure susceptibility. Moreover, modifications to the probes could be tested, for example cutting off the plastic insulation, thus making the probes smaller and placing the probe directly on the sample. Also increasing the distance between the probes could lead to a better signal as then the probe without sample will see less influence from the probe with sample. The most interesting point is to find out how the Hall probes behave in the pressure cell when submitted to more than ambient pressure. A setup for this measurement is available, too. If the measurements under high pressure work well, we will have established and alternative and probably better way of measuring superconductivity.

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Attachments

Where the data is stored

The results of all field-and temperature scans are stored on the LQM Kelvinox computer in C:\MEASUREMENTS\2010\08\ and are named 2010_08_xx.dat (xx from 1 to 45). The evaluation and all other data collected in Excel files are found in MyDocuments\sarah\....

In the logbook precise information about the single measurements is written down. The data from some easy measurements was only noted down in the logbook. The numbers in the overview over performed measurements refer to the page in the logbook where the experimental setup and measurement conditions are described.

The document "Some Measurements on Constructing a Susceptometer Made of Two Hall Probes" contains a lot of the data that proved invalid because the wrong coax configuration was used with the lock-in amplifier. Yet, the DC data is still valid, and a summary on it was done in there.

Overview over all performed measurements

At RT:

- 1a: Reaction of 5 types of Hall probes to 0T and approx. 0.1T constant external field (I Hall = 0.6mA)
- 2a: Reaction of Hall probes (type 1, 2, 3) to AC magnetic field (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)
- 4a: Reaction of double setup of Hall probes (type 2, 3) to AC magnetic field (I = 0.6 mA, OscAmp = 0.1V and 0.2V, OscFreq = 545.6 Hz)
- 20a: Reaction of alternative setup of Hall probes (type 3) to constant magnetic field (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)
- 26a: Reaction of alternative setup of Hall probes (type 3) to AC magnetic field (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)

- 30: Five possible configurations of two Hall probes (type 3) in constant magnetic field (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)
- 31a: Five possible configurations of two Hall probes (type 3) in AC magnetic field (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)
- 35a: Five possible configurations of two Hall probes (type 3) in constant magnetic field with samples (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)
- 36a: Five possible configurations of two Hall probes (type 3) in AC magnetic field with samples field (I = 0.6 mA, OscAmp = 0.1V, OscFreq = 545.6 Hz)

At 4K:

Single Hall probe:

- 17: DC Hall voltage response of probe (type1-5) to increased external magnetic field (I = 0.1mA)
- 17.1: DC Hall voltage response of probe (type 2, 4, 3) to increased DC Hall current at constant field (B = 1T)
- 17a: Hall voltage response of probe (type 2, 4, 3) to increased AC coil current at constant field (1T)
- 18: Hall voltage response of probe (type 2, 4, 3) to increased DC Hall current at constant AC field
- 19: Hall voltage response of probe (type 2, 4, 3) to change in oscillation frequency of AC current
- 19a: Hall voltage response of probe (type 2, 4, 3) to increased external magnetic field with AC changing field

Double Hall probes:

- 8a: Hall voltage response of probes (type1-5) to increased external magnetic field (I = 0.1mA)
- 10a: Hall voltage response of probes (type 2, 4) to increased DC Hall current at constant field (B = 1T)
- 12: Hall voltage response of probes (type 2, 4) to increased AC coil current at constant field (1T)
- 12a: Hall voltage response of probes (type 2, 4) to increased DC Hall current at constant AC field
- 12a: Hall voltage response of probes (type 2, 4) to change in oscillation frequency of AC current
- 13: Hall voltage response of probes (type 2, 4) to increased external magnetic field with AC changing field

Some additional measurements for comparisons between double probes at RT and at 4K can be found in the logbook on p. 14 onwards.

Double Hall probes in optimized configuration (see figure 5, 6, 7) (only for type 3) with lead sample

- 39 : Hall voltage response to increased external magnetic field around Hc with AC changing field (Configurations 1-5) (I = 0.1 mA, OscAmp = 0.1V, OscFreq = 545.6Hz)
- 40 : Hall voltage response for single probe (3) to increased external magnetic field in AC changing field (comparative measurement with correct configuration of the coax cable to the lock-in amplifier) (I = 0.1 mA, OscAmp = 0.1V, OscFreq = 545.6Hz)
- 40.1 : DC Hall voltage response to increased external magnetic field (Configurations 1-5) (I = 0.1mA)
- 40a : Hall voltage response to temperature scan (Configurations 1-5) with external magnetic field in AC changing field (I = 0.1 mA, OscAmp = 0.1V, OscFreq = 545.6Hz)
- 41a: DC Hall voltage response to temperature scan (configurations 1, 2,4) with external magnetic field (I = 0.1 mA, B = 0.025T)
- 40a : Hall voltage response to temperature scan (Configurations 1-5) with external magnetic field in AC changing field at higher oscillation amplitude (I = 0.1 mA, B = 0.025T, OscAmp = 0.3V, OscFreq = 545.6Hz)

Experiments in the pressure cell

- No measurements performed yet

References:

- http://www.chenyang-ism.com/ for product leaflet of all Hall probes, including their composition, range of applicability etc.
- Ashcroft/Mermin: *Solid State Physics* for critical field and temperature of lead sample