Optimisation of measuring magnetic properties of micro-structures using the magneto-optic Kerr effect

Måns Persson
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Abstract

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Magnetic storage means storage of data using magnetised medium and is widespread over the world today, especially in hard disk drives. Using this kind of storage requires knowledge about these materials. A way to study thin magnetic materials is to use MOKE(magneto optical Kerr effect). A Moke-system is a setup to measure thin magnetic films by shooting a laser and analyze the reflected beam. The purpose of this report is to document and if possible improve a MOKE-system, named HOMER. This includes temperature regulation, filters, amplifiers, optical chopper, Helmoltz coils and a laser. HOMER was documented and some changes were made. The PID-parameters were set successfully. A low pass filter was removed, which decreased the noise. Using an optical chopper and lock in amplifier however did not decrease the noise. A labview program was written to demagnetize the samples in a certain time which seemed to work properly. The hall probe in the system was successfully calibrated.
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1 Introduction

1.1 Background

In magnetic research today the magnetic optic Kerr effect (MOKE) is widely applied. MOKE describes how light is affected when reflected against a magnetic surface. More exactly the reflected light is rotated, depending linearly, on the magnetization of the sample. This relation makes it possible to measure magnetization of samples by using light, often a laser. Due to its simplicity and ability this method has become a basic tool and is widespread over the world. Especially when studying magnetic thin films. The application of MOKE on surface magnetism is often called surface magneto optic effect (SMOKE), and started in 1985. A cryostat can also be added to this setup to study the magnetization at different temperatures (1).

Examining magnetic properties of materials is necessary because of its widely applications. To store information on a hard drive disk an array of microscopic permanent magnets is set up. Magnetic recording is another example on use of magnetic properties of materials. This requires knowledge on a fundamental and application point of view (2).

1.2 Theory

1.2.1 Magnetic materials

A magnetic field is created when having a current (flow of electrons) through a conductor. According to the same principle a magnetic field is caused in atoms, by the electrons rotating around the nucleus, forming microscopic current loops (see figure 1). This cause an orbital angular momentum and an opposite directed magnetic dipole moment.

The value of the magnetic moment can be calculated with the formulas below:

\[ \mu = \frac{evr}{2} \]
\[ \mu = \frac{eL}{2m} \]

Where \( e \) is the elementary charge, \( v \) is the velocity of the electron, \( r \) is the orbital radius, \( L \) is the angular momentum of the electron and \( m \) is the mass of the electron.

In many materials the atoms are randomly orientated and thus these small magnetic fields cancel out each other. In other materials however an external magnetic field can cause the atoms to orientate in the same way and commonly create a magnetic field. In this case the material is said to be magnetized.

The electrons also rotate around their own axises, and have consequently an intrinsic angular momentum, called spin. This is a quantum mechanical phenomena, so it is not a spin in the classical sense. This also cause a magnetic moment to the atom. The electrons often circulates in pair with opposite spin which results in that the spin momentum cancels out. However materials with atoms having only one detached outer electron get a spin momentum.
Figure 1: The principle of angular momentum and magnetic moment in an atom. The electron with velocity $v$ and charge $e$ circulate around the nucleus with radius $r$. This can be considered as a microscopic current loop and cause an angular momentum $L$ and a magnetic dipole moment $\mu$.

Depending on the orbital- and spin magnetic moment and how the atoms are orientated the material will get different properties. These magnetic properties can be divided into three classes: Paramagnetism, diamagnetism and ferromagnetism.

In a paramagnetic material the atoms are randomly orientated and there is barely any net magnetic moment in the material. The magnetic field around a paramagnetic material is therefore very small. However when an external magnetic field is applied, the atoms will change directions and the net magnetic moments will align. The magnetic field inside the material will then be the sum of the external magnetic field and all the magnetic fields created by the magnetic moments in the atoms. Paramagnetic materials are attracted by external magnetic fields.

In a diamagnetic material, the net magnetic moment for all atoms are zero, when no external field is present. Although when a magnetic field is applied, the electrons around the atoms will cause a magnetic field in the opposite direction, in the same way that an induced current will give a magnetic field in the opposite direction. This is because there are still electrons around the nucleuses giving current loops, creating magnetic fields. For this reason diamagnetic materials are repelled by external magnetic fields.

In a ferromagnetic material, like iron, there are strong exchange interactions between the magnetic moments in the material. This causes different domains in the material where nearly all the magnetic moments are parallel. These regions get a net magnetization and are called magnetic domains. When an external
field is applied to these kinds of materials, the domains will align according to the external magnetic field. Even when removing the external field the magnetic domains will remain and the material will continue being magnetized. The order of the atoms when they are align can be disturbed by random thermal motion. For example a high temperature makes it harder for them to stay orientated and the magnetization of the material will decrease with an increased temperature. Only below a critical temperature, the Curie temperature, the alignment effect occur. Above this temperature the ferromagnetic order collapses and the material get paramagnetic instead(1)(5).

To reduce the magnetization of a ferromagnetic material to zero requires a magnetic field in the opposite direction. This is called hysteresis. Magnetizing and demagnetizing a material like this gives a special loop, called hysteresis loop, see figure 2. Depending on the material the hysteresis loop will differ. Some materials get a broad hysteresis loop which means that the external magnetic field needs to be strong in order to magnetize or demagnetize the material. Materials like this are called hard magnetic materials and are suitable for using as permanent magnets. The opposite is soft magnetic materials. These have narrow loops which means temporary magnets and the magnetization easily disappears when removing the external field(5). To permanently demagnetize a material completely to zero, one cannot just look at the hysteresis loop and set the external field to the coercivity value. At when having a hard magnetic material. When removing the external field in this case the material will go back to the remanence point. Instead the magnetic field should continue as before(being a sinus) but with a decreased amplitude. In this way the magnetic domains decreases and the magnetic moments in the material get randomized. In the end the amplitude of the curve will be so small that the sample is more or less demagnetized. The hysteresis loop at this point will be very small.

1.2.2 MOKE

The speed of light is different in a magnetized material compared to in other materials, or vacuum. This change in lightspeed is according to the formula

\[ v_p = \frac{1}{\sqrt{\epsilon \mu}} \]

where \( \mu \) is the magnetic permeability and \( \epsilon \) is the permittivity of the material. This will create fluctuations in the phase of the reflected light. For this reason the light rotate when being reflected against a magnetized material. As mentioned before this is the principle of a MOKE-setup and how this phenomena makes it possible to measure magnetism by using light. One can for example transmit p-polarized light at the sample which will cause the reflected light to rotate due to MOKE and consequently give an s-component to it. The magnitude of the s-component tells us the magnetization of the sample.
Figure 2: The hysteresis loop. The H-axis is the external magnetic field to magnetize the material. The vertical axis describes the normalized magnetization of the material. The dashed line in the middle shows how the material is magnetized the first time, called the virgin curve. The saturation point is a state when the magnetization of the material cannot be increased anymore. Thus an increased H-field will not have any affect after reaching that point. The remanence tells how magnetized the material is when the external field is set to zero again. The coercivity let us know the required external field to switch the magnetization direction of the material. Exactly at this point the average magnetic moment is zero.
1.3 The MOKE-system, HOMER

1.3.1 General description

The MOKE-system HOMER can be divided into three parts: The temperature regulating part, the optical part and the generation of a magnetic field to magnetize the sample. The optical part is about shooting a polarized laser beam at the magnetized sample and measure how much the reflected beam is rotated. The magnetic field part is about how to magnetize the sample. The temperature regulator makes it possible to regulate the temperature of the samples by using a cooling liquid and a heater. The liquid could be either helium or nitrogen but in this project we will work with nitrogen. A simplified schematic of the system can be seen in figure 3, with a picture of the cryostate in figure 4.

![Diagram](image.png)

Figure 3: Overview of HOMER. The laser(1) is shot and reflected against the sample(8). The reflected beam is measured by the detector(2). The nitrogen is kept in a tank(3) and transported to the sample by a pump(4). The nitrogen goes into the cryostat(5) in which the sample is at the bottom. Around the cryostat there is vacuum made by another pump(6). In the cylinder(7) there are Helmholtz coils to magnetize the sample. A μ-metal shielding is used to shut out the magnetic field from the earth.
Figure 4: The cryostate used in HOMER. In the bottom we see the magnetic sample(1). The nitrogen flows inside until just above 2 and then back up again. The lump in the bottom where the cryostat is a bit thicker, is made to keep the temperature more stable. It is made of copper which has good thermal conductivity. Inside there is placed a resistor which works as the heater.

1.4 Purpose of the project

The goal of this project is to optimize and describe HOMER which is a MOKE-system at the Ångström laboratory. The system was built around fifteen years ago. However the one who built it does not work there anymore and there is no proper documentation of the system. Therefore the system needs to be documented and optimized to get the best results when measuring. High noise levels for example can give the measurements of very small magnetic field strength a large margin of error. The project can be divided into three main parts: documenting the setup and electronics, reduce the noise in the received signal and improve the temperature controller. The PID-parameters in the temperature regulator needs to be set properly. It is also necessary to find a good gas flow of nitrogen by changing pressure and the vault to the nitrogen tank. This makes it possible to set the temperature to a specific value and reach that temperature
quicker. A careful documentation of the MOKE-system will be made in order to investigate it and see if some parts can be improved. For example components as filters, Helmholtz coils etc. The last part is to improve the noise level. This will be tried by using a chopper and lock in amplifier in order to exclude light from the surroundings in the signals. In the end some measurements will be made and hysteresis curves analyzed.

2 Electronics of HOMER

2.1 Overview

A documentation of the system was made. Basically how everything was connected and the values of the components (see figure 5). Some components were inside home made boxes, for example the low pass filter. After being opened the values of the components were read if having them written, otherwise measured.

Figure 5: Overview of the electronics in the MOKE-system. All the components and how they are connected. 1 - computer. 2 - BNC-2110 national instruments. 3 - lowpassfilter. 4 - Amplifier(SENTEC, monopower amplifier, ACM 1 A) 5 - Homemade box which contains an amplifier for the hall probe, 6 - Hall probe, 7 - Helmholtz coils, 8 - lock in amplifier(SR830 DSP, Stanford research systems), 9 - Detector, Stanford research systems, model SR570
2.2 Filtering properties of the Helmholtz-coil

Figure 6: Schematic of helmholtz coil with dimensions.

As the Helmholtz coil (see figure 6) has an inductance, the reactance will be increased with the frequency. This is because the reactance $X_L$ in the coil is described as

$$X_L = j\omega L$$  \hspace{1cm} (1)

where $L$ is the inductance measured to $30mH$. The coil also has a resistance in series, because of the resistivity in the wire which was measured to 6 Ohm. We see that we get a real value from the resistivity and an imaginary from the reactance. Therefore the impedance of the coil has a complex value which is $Z = r + j\omega L$. The absolute value of this is:

$$|Z| = \sqrt{(\omega L)^2 + r^2}$$  \hspace{1cm} (2)

Where $r$ is the resistance of the copper wire. The current $I$ in the wire will then be, because of Ohm’s law $I = \frac{U}{Z}$, where $U$ is the voltage over the coil. The magnetic field in the center generated by a helmholtz coil when a current flows through it, is described as

$$B = \left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 n I}{R}$$  \hspace{1cm} (3)

Where $n$ is the number of loops in the coil, $R$ is the radius and $\mu_0$ is the magnetic constant. This is derived in the appendix. Because the impedance is $Z = r + j\omega L$ we know because of Ohm’s law:

$$B = \left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 n U}{R * (r + j\omega L)}$$

If we extend this with the complex conjugate, we will get:

$$B = \left(\frac{4}{5}\right)^{3/2}\frac{\mu_0 n U * (r - j\omega L)}{R * (r^2 + (\omega L)^2)}$$
This, being a complex number, will give us a phaseshift between the voltage and the magnetic field that is equal to the angle between the imaginary and the real part of the equation. The total magnetic field can be calculated by taking the absolute value of the equation, as in equation 4.

\[ B = \left(\frac{4}{5}\right)^{1/2} \frac{\mu_0 n U}{R \sqrt{(\omega L)^2 + (r)^2}} \]  

(4)

To see how the magnetic field depends on the frequency of the voltage over the wire, data is simply taken from an oscilloscope measuring the voltage and from the hall probe (#6 in figure 5) measuring the magnetic field. The magnetic fields dependency on the frequency can be seen in figure 7. Because of the impedance there will also be a phaseshift between the voltage over the coils and the magnetic field. This phase shift will be equal to the angle between the real part and the imaginary part of the impedance. To calculate the phaseshift equation 5 can be used.

\[ \theta = \arctan \frac{\omega L}{r} \]  

(5)

Where \( \theta \) is the phase shift. The theoretical and measured phase shift can be seen in figure 8.

![Figure 7: Magnetic field vs frequency at the coils. The magnetic field was measured with a hall probe. The cutoff frequency is indicated with a vertical line, at around 30Hz.](image-url)
Figure 8: Phaseshift between the magnetic field and the voltage over the coils.

2.3 Filters

There were two unknown boxes that were opened. The first one (see figure 5, box 3) was a lowpass filter which had a resistor at 50 ohm and a capacitor at 2.2 $\mu$F. Through this we got the cut off frequency to 10kHz. This low pass filter seemed unnecessary. First of all we could not find any reason why to prevent high frequencies. Moreover the helholtz coils will work as low pass filters and had a cutoff frequency at 30Hz. Therefore the low pass filter was removed which actually improved the system with less noise as a result.

The other box (see figure 5, box 5) was opened and studied. This was the box connected to the Hall probe. It contained a quite complicated PCB and the components was not available. Considering how it was connected to the hall probe it should be an amplifier.

2.4 Measurement devices

A lock in amplifier (SR830 DSP, Stanford research systems) was tested to see if more exact magnetic fields could be set, and measurements could be more precise. The lock in amplifier was unstable at higher frequencies, where it was hard to get good measurements of the amplitude. Although it was helpful in measuring the phase shift. The phaseshift had been measured manually with an oscilloscope prior to the lock in. The phaseshifts dependency on frequency when using the lock in amplifier can be seen in figure 9. The amplitudes dependency on frequency when using the lock in can be seen in figure 10.
Figure 9: Phaseshift between the magnetic field and the voltage over the coils while using the lock in amplifier.

Figure 10: Amplitude of the magnetic field and the voltage over the coils while using the lock in amplifier.
3 Temperature regulation

3.1 Introduction

The temperature regulator in HOMER mainly aims to cool the samples. The cooler of the MOKE-system consists of a container of liquid nitrogen connected to a pump. Nitrogen then flows from the container through a double-piped transfer rod, with a valve that can be adjusted, into a cryostat where the sample is placed (see figure 4). Inside the cryostat there is almost a vacuum (around $10^{-8}$ mbar), to prevent thermal conductivity with the surroundings. This vacuum is created with a turbo pump. The temperature is regulated with a PID-regulator and is controlled by the values of P, I, D. Furthermore the temperature depends on the flux of nitrogen. This can be varied by changing the needle valve controlling the intake of liquid into the transfer rod or change the pressure made by the pump. The gas flow and pressure created by the pump are important factors. The flux has to be high enough to cool the sample down to the lowest temperatures at around 80K but too high flow makes it hard for the heater to heat up the sample fast enough when increasing the temperature and also to reach the highest temperatures at about 350K. Studying the heating power is a way of finding a good pressure and gas flow. To much heating power for example indicates that the flux is too high and the heater may get problems with reaching temperatures, either to slow or not at all. The gas flow should then be decreased and/or the pressure of the pump increased. A gas flow and pressure that keep the heating power between the interval 20-80 % is good, but the more in the middle of this interval the better.

There is a copper boulder by the sample, with a resistor inside of it. While having a current though the resistor the boulder is heated up and thus this works as the heater. When having the PID-parameters set correctly one can set the desired temperature of the sample and get there with smaller overshoot and in shorter time. The ideal PID-parameters might change depending on temperature.

3.2 Method

The valve to the nitrogen container was set to a low value, but still high enough so that the gas flow was stable. If the gas flow is too low it might get unstable. With this gas flow, temperature series at different pressures were made and the heating power was measured.

To optimize the temperature regulator the PID-parameters had to be set correctly. This was done by following the manual, ITC503 for the intelligent temperature controller(1). The first parameter to be set was P. The D-value was then set to zero and the I-value to 140 (in minutes), which was much bigger than the expected response time for the system. An I-value like that will have no effect and thus P was the only parameter left. P was set to a big value and was then decreased until the temperature curve started to oscillate around some value (see figure 11). The I-value was then set to the period time of these oscillations, in minutes. P was increased until the oscillations just ceased, then it was doubled. The current values of P and I at this point were our starting values. After this the parameters was adjusted freely by studying the temperature curve until the optimized parameters are found. The temperature was then simply
increased with steps of 2K and 5K and the curve of the actual temperature was observed. The PID-parameters with the smallest overshoot and time to stabilization was chosen. Figure 12, 13 and 14 shows how the curve varies depending on the values of P, I and D. The PID-parameters were set for three different temperature intervals, $< 150K$, $150K - 250K$ and $> 250K$, see table 1.

### 3.3 Results and discussion

When the PID-parameters were set the first time we had some problem with the cooler system. When having a to low gas flow the pressure was unstable which resulted in unstable temperature. However when the gas flow was increased too much the heater did not have enough power to heat the system up and the temperature was again unstable. We found a value for the gas flow in the middle at 26 % which worked and set the PID-parameters for this value. However the pump was replaced since it did not work properly and the PID-parameters had to be set again. They were almost the same, as can be seen in table 1 and table 2, but the gas flow was decreased to 25%. As can be seen in figure 14 the D-value did not improve the stabilization curve, therefore it was set to zero. For the gas flow at 25% three different temperature series were made with different pressures, see figure 15. As we can see the middle line at 600 mbar is the best since the heating power is working around 40-60 % the entire temperature range. The heating power differed a bit from time to time doing the measurements, even for the same pressure and gas flow. This probably depended on problems with the vault, which not seemed to reach the value that was set every time. Since we could only set the gas flow and not read it, it was hard to know what the actual value was. However these error was small enough to keep inside the interval 20-80 % for 600 mbar because of the wiggle room. Thus a gas flow of 25 % and pressure of 600 mbar should keep the heating power in the desired interval. Would it still be a problem the pressure can be adjusted until the heating is correct for the present temperature by looking at figure 15.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>P</th>
<th>I</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>80-150</td>
<td>7</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>150-250</td>
<td>5</td>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>250-350</td>
<td>3.5</td>
<td>0.4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: PID values for different temperatures.
Figure 11: The oscillations of the temperature curve when only having P at a certain value. The period time for these oscillations was used to set I.
Figure 12: Temperature stabilizing curve with different P-values. I=0.3, D=0, 27% gasflow.

Figure 13: Temperature stabilizing curve with different I-values. P=5, D=0, 27% gasflow.
Figure 14: Temperature stabilizing curve with different D-values, P=5, I=0.3. 27% gasflow.

Figure 15: Heating power vs temperature at different pressures. 25% gasflow.
4 Magnetization of materials

4.1 Demagnetization of the samples

To make measurements on magnetized materials it is important to be able to demagnetize them occasionally. The magnetized sample was demagnetized by gradually reducing the external field. As can be understood from the hysteresis loop (figure 2) the external field cannot just be set to zero. The amplitude of the AC current is instead decreased slowly, so the magnetization moves closer to zero. When reducing the external field, the hysteresis loop along the vertical axis will decrease. This will reduce the magnetization of the sample and thus reduce the hysteresis loop along the vertical axis. A program was written in Labview to demagnetize the sample in a certain time. This program linearly reduced the amplitude of the AC current in the Holmholtz coils to zero, see figure 16 and figure 17.

![Figure 16: Four hysteresis curves, when demagnetizing the sample. In total there was 53 hysteresis loops but only number 1, 25, 50 and 53 is shown to make it easier to see.](image)
4.2 Calibration of the hall probe

The hall probe was calibrated by using an extra temporary gauss meter. The sample was then removed and replaced by an extra gauss meter. It was placed in the middle of the coil, just behind the usual hall probe where the sample use to be. Then the calibration could begin. The voltage over the hall probe is proportional to the magnetic field, and thus we get a linear correlation between them (see figure 18 and 19). By varying the outgoing voltage and plot it against the resulting magnetic field, the slope of the curve and offset voltage can be determined. The temperature of the wire affect the resistivity so to avoid this only small currents (small voltage) were used in the coils. Before the calibration was made the demagnetization program was ran. This reduced the magnetic field, probably because it demagnetized the setup.
Figure 18: Hall voltage vs magnetic field. The magnetic field was measured with a gauss meter, at 101 points in the interval -1 to 1 V over the Helmholtz coils.

Figure 19: Voltage over the Helmholtz coils vs magnetic field. The magnetic field was measured with a gauss meter at 101 points in the interval -1 to 1 V over the Helmholtz coils.
4.3 Kinds of measurements

There are basically two kinds of measurements one can make on the samples. Either an AC current is going through the Helmholtz coils while measuring the magnetization of the sample. The other way is to have a DC current that changes with certain steps and measure the magnetization between these steps.

4.4 Discussion

The demagnetization of the sample is shown in figure 16 and 17. In figure 16 some of the hysteresis loops are plotted in order to show how they change when the sample gets demagnetized. We can see that both the external magnetic field and the magnetization of the sample decreases, which was expected. The last hysteresis loop is only a dot which means that the sample is completely demagnetized. Figure 17 shows the results from the same measurements but in another way. The vertical axis shows the normalized amplitude from every hysteresis loop (the maximum value of the magnetization) and the horizontal axis shows time instead of number of hysteresis loops. Every loop took 20 seconds. We can see that the demagnetization (amplitude of the curve) is not linearly decreasing, which the current in the Helmholtz coils was.

Figure 18 and 19 shows the results from the calibration. We see that we have an off set voltage, even when the applied magnetic field is zero.
5 Improvement of noise level in the optical part

5.1 Introduction

In figure 3 we see the basic principle of how the laser is used to measure magnetization. To measure the reflected laser beam an amplifier is used. This way of detecting the signal is simple, the intensity of the light just increases by the amplifier. However the amplifier does not only increase the power of the signal from the laser. Light from the surroundings also gets increased which causes noise to the measurements.

5.2 Reducing noise using an optical chopper and lock in amplifier

To reduce noise in the received signal one can use a chopper and lock in amplifier which was tried in HOMER. The idea is to use a chopper, which aims to give the laser a certain frequency. It is a small rotating wheel with stripes of gaps. It is placed between the laser and the sample and depending on the angular velocity of the chopper the laser gets different frequencies. A lock in amplifier is a amplifier that can extract a signal with known specifications from a very noisy environment. In our case the shopper gives the laser a certain frequency and the lock in amplifier extract light only with that frequency. In this way the measurements hopefully will not get affected by lights from the surroundings. Measurements were done both with and without the shopper to see if it improved them or not. The shopper can only be used when having a DC current in the Helmholtz coils. As we can see in figure 20 the chopper did not improve the measurement. It seems like using the chopper works equally good as not having one.

6 Conclusion

A Low pass filter was removed (#3 in figure 5) which decreased the noise. The cutoff frequency for the Helmholtz coil was around 20Hz, which matched the theoretical cutoff frequency as well. The phase shift between the magnetic field and the voltage over the coil increased with the frequency.

The gasflow (vault) should be set to around 25 and the pressure to 600 mbar in order to get the optimal temperature regulation. However the vault did not work perfectly and the gasflow seemed to vary from time to time even when having the same value set. This can be adjusted by changing the pressure, using figure 15 to see the supposed heating power for that temperature. Another way is to close and open the vault completely before setting the value.

The labview program that was written to demagnetize the materials worked properly. It seemed like the hysteresis curves when having an AC current gave better result than using DC. Using a chopper and lock in amplifier did not improve the system. It was as much noise in the received signal as using a normal amplifier. However only one frequency was tried, 1425Hz. Maybe improvements could be made with other frequencies. Another improvement could be to set the frequency directly in the laser instead of using a chopper.
7 Populärvetenskaplig sammanfattning

8 References

Figure 21: The theoretical plot of how the low pass filter affect the amplitude.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>P</th>
<th>I</th>
<th>D</th>
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<td>250-350</td>
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Table 2: PID values got with the old pump.

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<td>800</td>
<td>380</td>
<td>67 (80)</td>
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Table 3: Pressure vs heating power in different temperatures
Table 4: The ideal PID-parameters got when having the new pump

<table>
<thead>
<tr>
<th>Temperature (K)</th>
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Table 5: Temperature and heating power at 400 mbar with 25% gasflow.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Heating power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>43</td>
</tr>
<tr>
<td>130</td>
<td>48</td>
</tr>
<tr>
<td>180</td>
<td>52</td>
</tr>
<tr>
<td>230</td>
<td>55</td>
</tr>
<tr>
<td>280</td>
<td>60</td>
</tr>
<tr>
<td>330</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 6: Temperature and heating power at 600 mbar with 25% gasflow.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Heating power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>22</td>
</tr>
<tr>
<td>130</td>
<td>27</td>
</tr>
<tr>
<td>180</td>
<td>41</td>
</tr>
<tr>
<td>230</td>
<td>45</td>
</tr>
<tr>
<td>280</td>
<td>47</td>
</tr>
<tr>
<td>330</td>
<td>50</td>
</tr>
<tr>
<td>380</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 7: Temperature and heating power at 800 mbar with 25% gasflow.

<table>
<thead>
<tr>
<th>Pressure gf = 30% (mbar)</th>
<th>Temperature (K)</th>
<th>Heating power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>90</td>
<td>38</td>
</tr>
<tr>
<td>250</td>
<td>120</td>
<td>38</td>
</tr>
<tr>
<td>250</td>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>250</td>
<td>180</td>
<td>40</td>
</tr>
<tr>
<td>250</td>
<td>210</td>
<td>42</td>
</tr>
<tr>
<td>250</td>
<td>240</td>
<td>44</td>
</tr>
<tr>
<td>250</td>
<td>270</td>
<td>47</td>
</tr>
<tr>
<td>250</td>
<td>300</td>
<td>49</td>
</tr>
<tr>
<td>250</td>
<td>330</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 8: Pressure vs heating power in different temperatures
9.1 Derivation of the theoretical magnetic field inside helmholtz coil

From one of the coils, Biot-Savarts law will give the magnetic field on the x-axis as:

\[ B_1(x) = \frac{\mu_0 n I R^2}{2(R^2 + x^2)^{3/2}} \]

For a single coil with one loop. Because of the Helmholtz coils dimensions we know that the center of the coils is at \( x = R/2 \). The Helmholtz coil consists of two identical coils at the same distance from the center giving us:

\[ B(R/2) = 2B_1(R/2) = \frac{2\mu_0 n I R^2}{2(R^2 + (R/2)^2)^{3/2}} \]

This is equal to:

\[ B(R/2) = \frac{\mu_0 n I R^2}{(5R/4)^{3/2}} \]

Divide by \( R^2 \) in numerator and denominator gives:

\[ B = \left( \frac{4}{5} \right)^{3/2} \frac{\mu_0 n I}{R} \]