Instrumental Developments for a
Surface Magneto-Optical Kerr Effect (SMOKE) Magnetometer

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ABSTRACT

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The Surface Magneto-Optical Kerr Effect (SMOKE) magnetometer is an instrument used to measure the out-of-plane magnetization of thin films made of ferromagnetic materials using polarized visible light. It does this by taking advantage of the Kerr effect which is a magnetic-optical interaction where the polarization of the light reflected from a magnetic surface is rotated approximately proportionally to the amount of magnetization in the material. We use the instrument to map hysteresis loops in ferromagnetic thin film multilayers by applying a varying external magnetic field to the sample while simultaneously measuring the polarization rotation. My project has consisted of upgrading the physical SMOKE apparatus: we have improved the mechanical stability and introduced new features that will allow us to alter the incident angle between the sample and the polarized light, as well as give us the ability to translate samples so that we can study different sections of the samples without having to remount them.

Keywords: Surface Magneto-Optical Kerr Effect, ferromagnetic thin films, magnetometer, hysteresis loop

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1. Introduction

The surface magneto-optical Kerr effect (SMOKE) magnetometer is an instrument designed to measure the magnetization of a material under the application of an external field. If the magnetic field is cycled from positive to negative and back to positive direction, one obtains a magnetization loop. When the ascending and descending branches of the magnetization loop do not match, the loop shows “hysteresis’ and is then called a “hysteresis loop”. Hysteresis is a characteristic of ferromagnetic materials and results from the formation and motion of magnetic domains within the material. In the absence of an external field, the magnetic domains would typically alternately align in opposite directions so the net magnetization is close to zero. When an external magnetic field is applied, the magnetic domains begin to align with the applied field. The greater the applied field, the more of these magnetic domains will be aligned, increasing the internal magnetization of the material. This continues until all the domains have aligned themselves with the applied field, at which point the material is uniformly magnetized and is said to have reached saturation. As the applied field is progressively decreased, these magnetic domains start to revert to their original alternate ordering, but not at the same rate at which they were originally aligned. Instead, the domains will remain saturated until the applied field is reduced to where the sample begins to experience nucleation, which is at a field value significantly below the original field value required to reach saturation, as illustrated in Figure 1. As the applied field approaches zero and then reverses direction (negative field value) the ferromagnetic material passes through the coercive point where the magnetic domains are randomly oriented and cancel each other out so the net magnetization is about zero. The same process is then repeated with a negative field to map out the other half of the hysteresis loop creating what is referred to as a ‘major loop’ [1].

Mapping the hysteresis loops of various materials is important in the research and production of various technologies, especially in the fields of computing and data storage where thin ferromagnetic films are used as a support to store data. In these applications it is important to know how much field is required to align the domains in the material, how much field is required to reverse them, and the amount of magnetization that will remain when the field is removed [2].

One of the difficulties in obtaining hysteresis loops is measuring the internal magnetization of the ferromagnetic material independently of the applied field. The SMOKE provides one avenue to do this by taking advantage of the Kerr Effect. The Kerr Effect is a magneto-optical effect where polarization of the light reflecting off a magnetic surface is rotated proportionally to the amount of internal magnetization (to a first approximation) [3]. By reflecting a polarized laser off a sample and measuring the degree of rotation of the light we get access to the magnetization of the sample. Since the light is not directly affected by the applied magnetic field, we can measure the magnetization of the sample while it is being influenced by the applied field, and successfully plot the hysteresis loop.

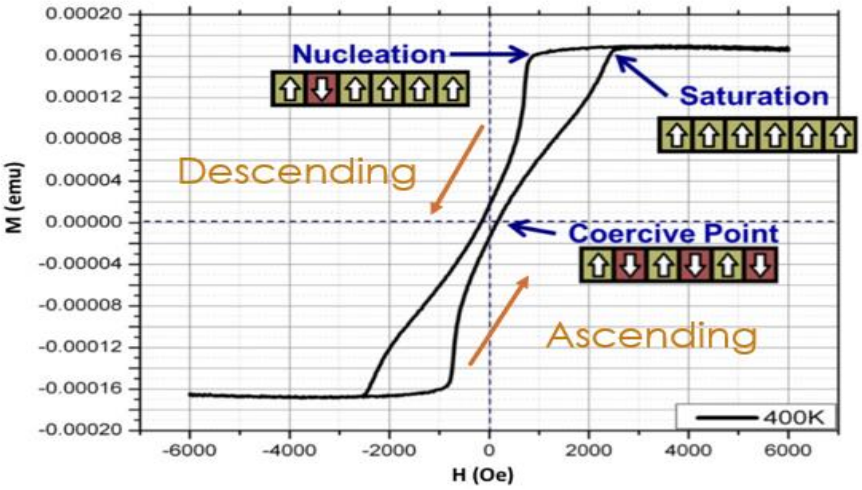

Figure 1 An example of a hysteresis loop showing key features such as the coercive point, saturation and nucleation, and examples of domain configurations for each of those features. – courtesy [4]

2. Methods

2.1 Our Sample

Our SMOKE instrument was developed to study ferromagnetic multilayer thin films. A Magnetic Force Microscopy (MFM) image of one of these thin films is shown in Figure 2. The light and dark regions in this image show magnetic domains of opposite magnetization directions (pointing up and down, out-of-plane). The size and morphology of these domains can be affected by an external magnetic field like the one created by the SMOKE.

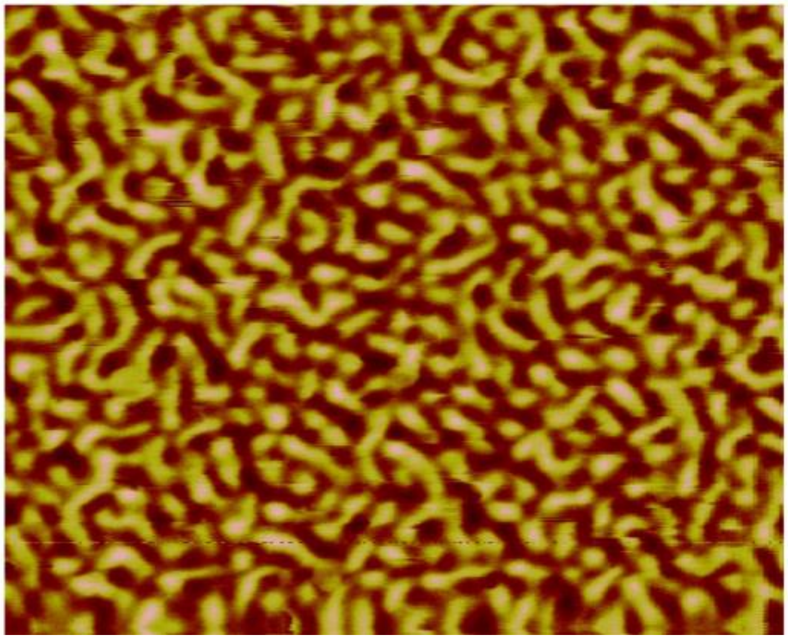

Figure 2 An MFM (Magnetic Force Microscopy) image of a Co/Pt multilayer sample showing the magnetic domains inside a ferromagnetic sample. – courtesy [4]

Figure 3 shows the difference between in and out-of-plane domains. In the case of our samples the domains are all exhibiting out-of-plane magnetization, or “perpendicular magnetic anisotropy (PMA)”.

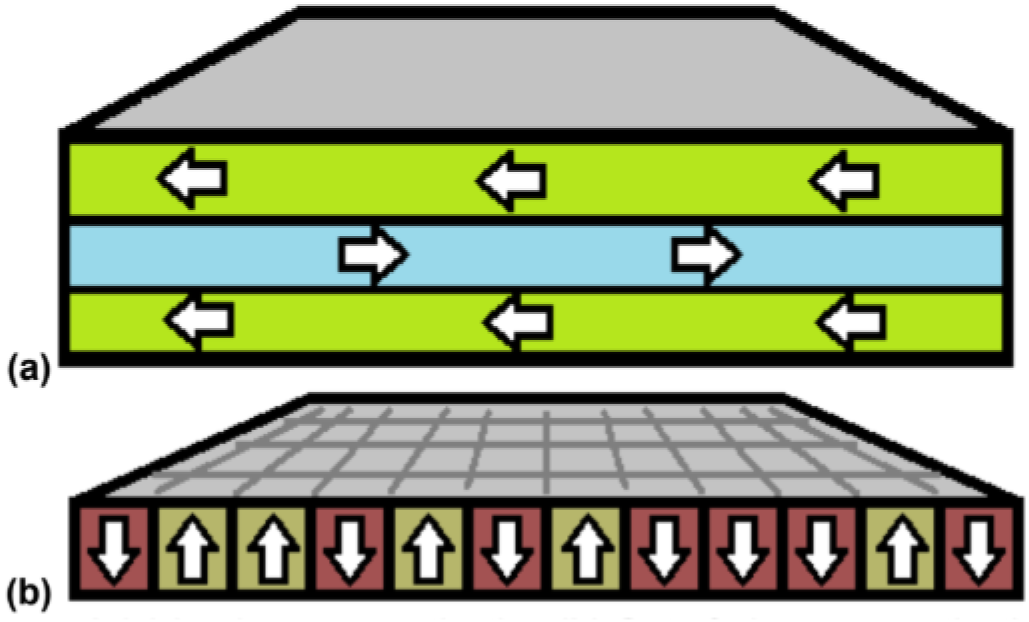

Figure 3 An example of (a) in plane magnetization and (b) out-of-plane magnetization – courtesy [4]

Some of our samples are wedge-shaped, where the thickness of the film gradually varies. Because the magnetic behavior may be thickness-dependent, and given that the SMOKE probe is a smaller laser beam, a wedge shape allows us to study the dependence of hysteresis loops on thickness, assuming the laser beam can be moved across the wedge.

2.2 Mechanical Setup

Our mechanical setup is built around a water-cooled electromagnet. This electromagnet has a resistance of about 1 Ohm. When powered at our maximum capability of 40 V and 40 A, the electromagnet produces a field of 9,344 G (Gauss) between its poles. This is sufficient to reach the saturation points of several of the samples we are studying.

Extending between the two poles of the magnet is the optical board on which optical elements are mounted. This provides a base which is both secure and allows for flexibility to rearrange the optics as needed.

Our optical setup utilizes a 635 nm collimated laser diode, two polarizers, six mirrors and a beam splitter as shown in Figure 4. Our light is produced by the laser diode where it is collimated but not polarized. We immediately polarize the light completely in the P-direction (that is oriented in the plane of reflection, which is the plane of representation in Figure 4) using our first polarizer. The light is then sent through a 50:50 beam splitter. 50% of the light is reflected to Photodiode-1 which will be used to monitor the incoming light and correct for fluctuations in the beams output, while the other half reflects off a mirror and illuminates the sample.

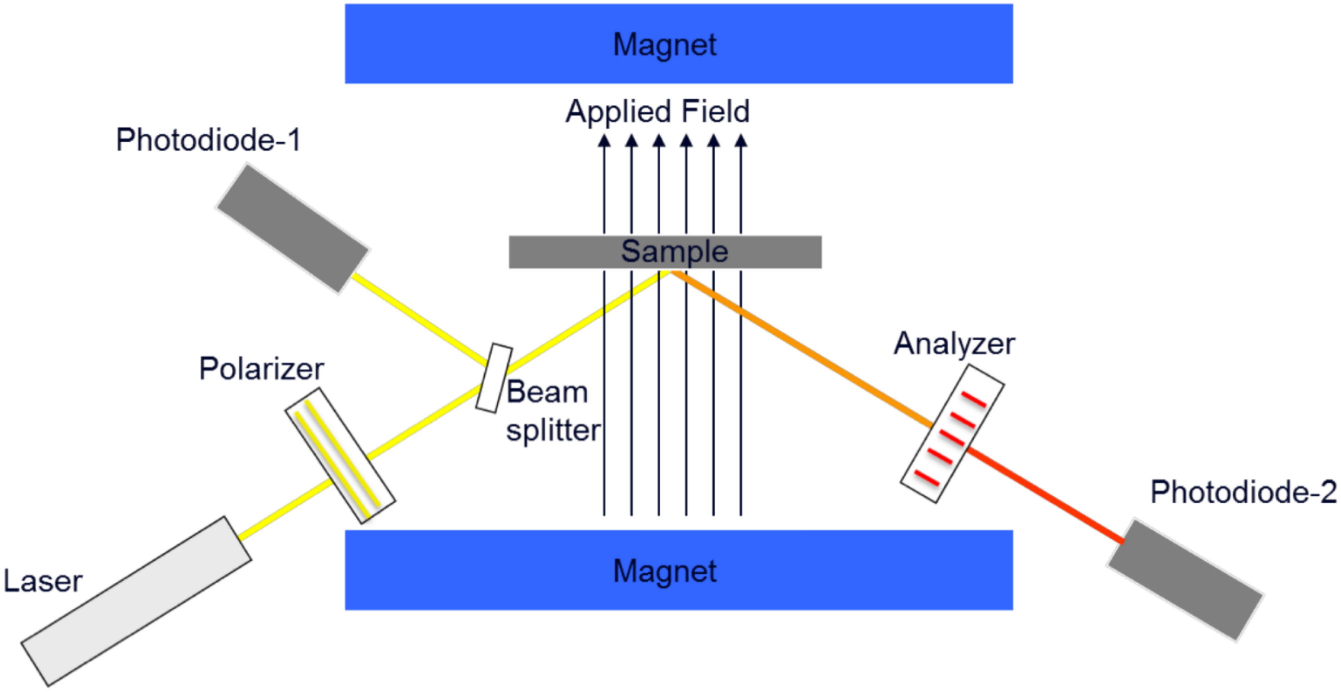

Figure 4 A simplified diagram (not showing the position of the mirrors) of the basic layout of the laser, sample and optics used in our SMOKE setup – courtesy [4]

The P-polarized light reflects off the sample and by the Kerr effect is rotated proportionally to the magnetization of the sample. The beam is still polarized mostly in the P-direction but now has a small degree of S-polarization as well (S-direction is perpendicular to the reflection plane, and parallel to the surface of the sample). Using the small angle approximation, it is assumed that the S- component is proportional to the magnetization in the material.

After reflecting from three more mirrors the beam passes through a second polarizer to isolate the S-polarized portion of the light. As a result from a former optimization study, this polarizer has been set to an angle of 16° from the S-direction rather than completely in the S-direction (extinction) since it was found experimentally to be a good compromise to optimize the signal by making sure enough light comes through and not be drowned out by the background noise of the photodiode, but also not be distorted by having too much P-polarized light come through to drown out the S-polarized portion [4].

Two photodiodes are necessary in this setup because the beam intensity from our laser diode is not constant. It was found that the intensity of our diode tends to drift during the first half hour of operation. We can avoid the data distortion caused by this drift by powering on the laser at least a half hour before we take measurements. However, it was also found that our beam intensity fluctuated due to the magnetic field created by our electromagnets, and that the relation was non-linear. Thus, rather than try to correct for the fluctuation mathematically, we use the first photodiode to monitor the beam intensity before the beam reflects off the sample and use this to normalize our data.

2.3 Electrical Setup

To get the maximum desired field from our electromagnet we need to drive it at 40 A. Because the electromagnet has a load resistance of ~1 Ohm this means we also need a maximum voltage of 40 V. To obtain these voltages, we use four Kepco 20-20M bipolar power supplies arranged in a master-slave configuration. Each of these power supplies can deliver +/- 20 A and +/- 20 V. By placing two of these power supplies in series we can double their effective output from +/-20 V to +/-40 V. We then add in a parallel branch with two more power supplies. This doubles our effective current output from +/- 20 A to +/- 40 A giving us our desired total output. A diagram of this setup is shown in Figure 5.

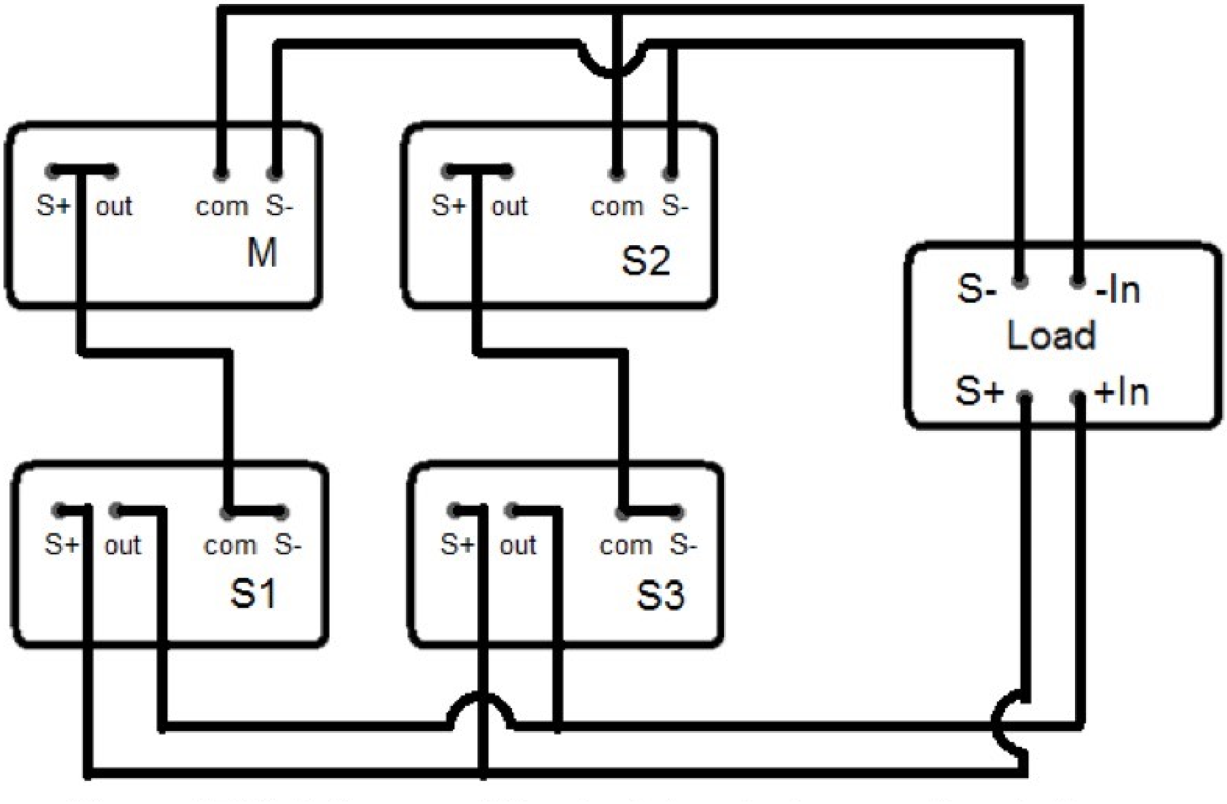

Figure 5 Electrical wiring diagram for our four bipolar power supplies showing the Master (M) and Slaves (S1, S2 and S3) in a circuit with two power supplies in series in each of two parallel branches. – courtesy [4]

Our power supplies are unique in that they are bipolar, meaning that they can pass smoothly from a positive voltage or current output to a negative one without having to disconnect or rearrange any wiring [5]. This is important for the SMOKE's operation since it allows us to change the direction of the field created by our electromagnet during our measurements so that we can measure an entire magnetization loop.

Our setup uses a master-slave configuration as shown in Figure 5. In this configuration the power supply designated as "Master" has its voltage or current output controlled either manually through the analogue controls on the front of the power supply or remotely by the computer using a Bit 4886 card and 8 pin Bus connection. As shown in Figure 6, Slave One (S1) is setup to copy the Master (M) voltage, Slave Two (S2) copies the M current, and then Slave Three (S3) copies the S2 current. This is accomplished through connections between PC12 connectors attached behind each power supplies, as shown in Figure 7.

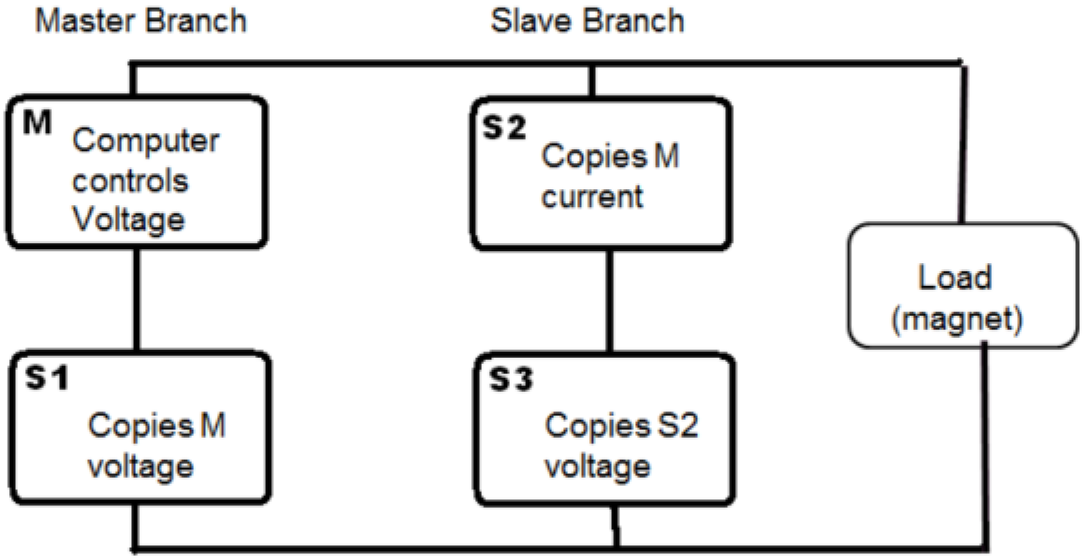

Figure 6 Diagram showing the Master-Slave configuration and the roles of each power supply – courtesy [4]

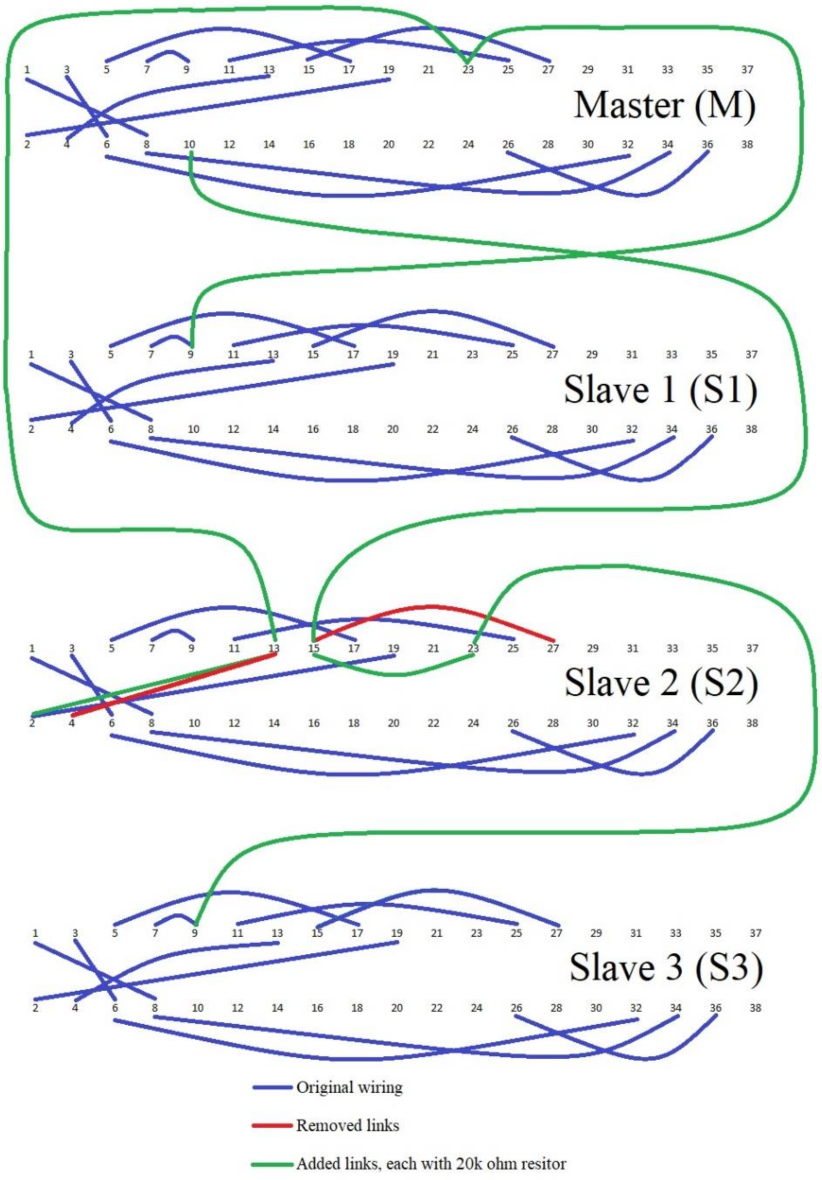

Figure 7 Wiring diagram for the PC12 connectors showing the original, removed and added links to allow the power supplies to operate in the desired Master-Slave configuration.

2.4 LabVIEW

In our setup, we use a LabVIEW program to control the voltage output of our power supplies. As discussed in the Electrical Setup section, the LabVIEW program sends voltage commands to the Master only, and then the Master communicates with the other power supplies.

The LabVIEW program receives back from the Master power supply measurements of the actual voltage and current outputs. The LabVIEW program also receives measurements from both photodiodes of the amount of light they are receiving.

Using the calibration shown in Figure 8, which was derived experimentally [4] we can convert the current output measurement being returned by the power supplies to a field value for the external field being created by our electromagnet.

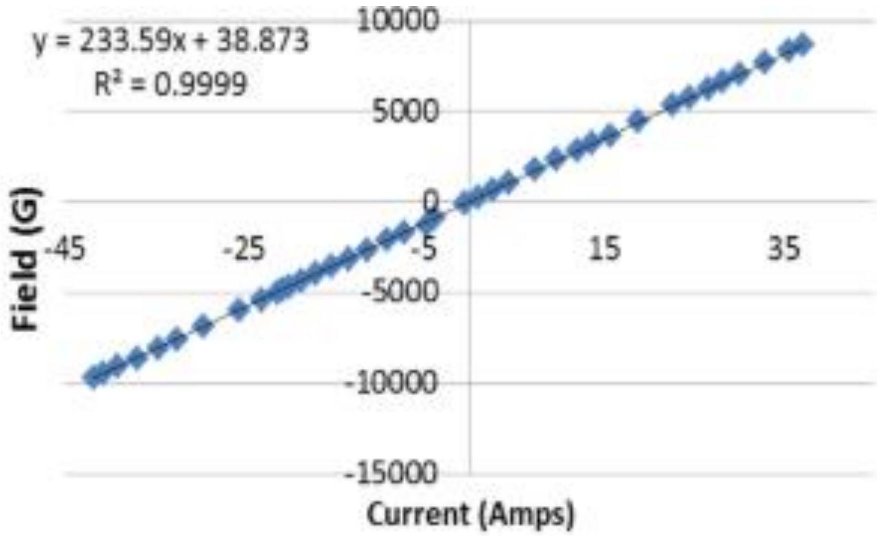

Figure 8 Graph showing the experimentally gathered data and resulting fitted line we use to determine the field from the current supplied to the magnet – courtesy [4]

The LabVIEW program we use is set to run a series of “loops” where it sends commands to the Master power supply to incrementally increase the voltage until it reaches a set maximum value, then decrease the voltage incrementally to a set minimum value. It repeats this process for a set number of loops while recording at each step the external field value and measurements from both photodiodes. This information is later used to plot the hysteresis loop of the sample being measured. Figure 9 is an example of a hysteresis loop plotted and normalized from the data collected by the SMOKE.

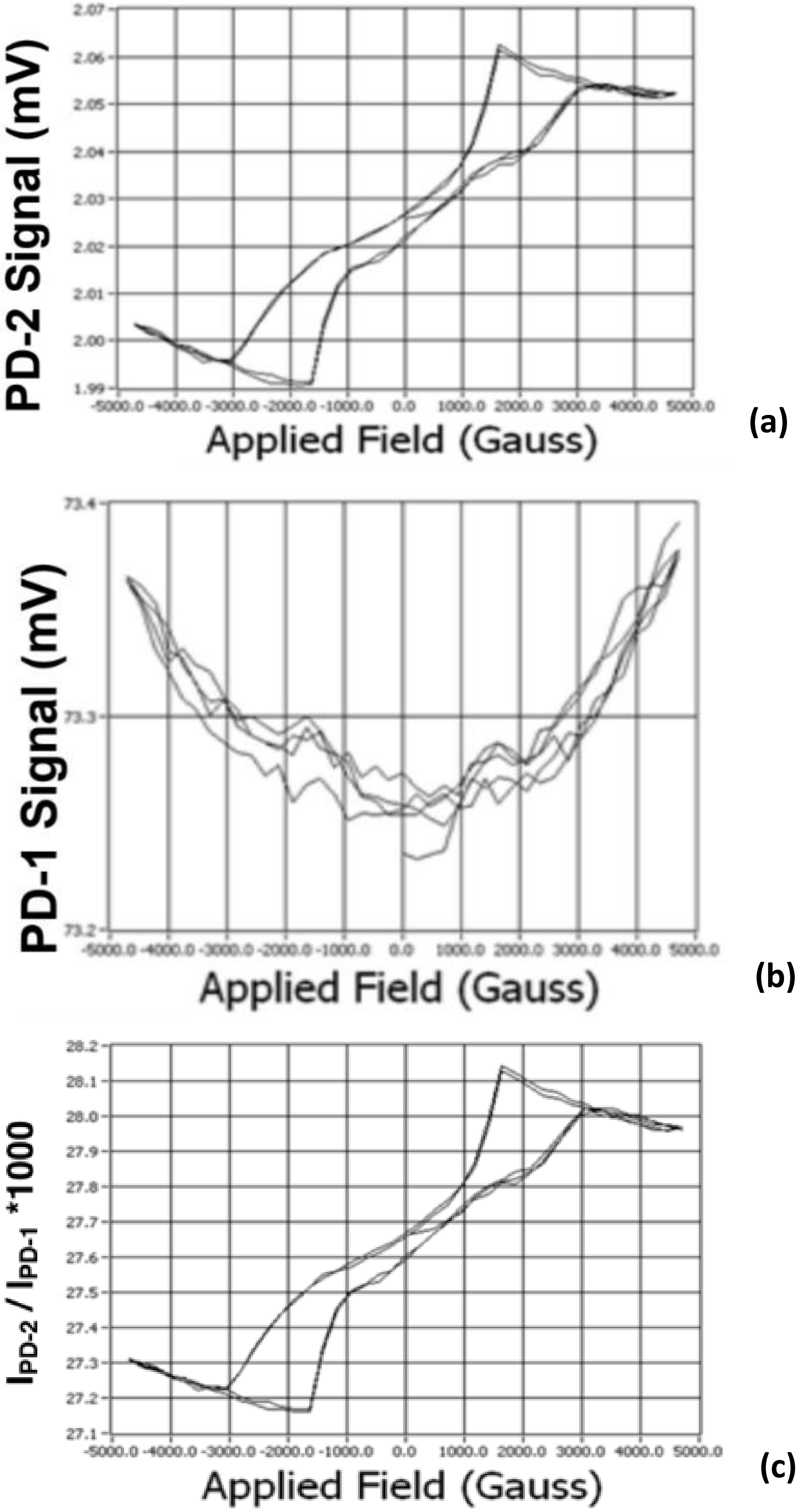

Figure 9 Example of a hysteresis loop created using the data collected by the SMOKE. (a) shows the signal arriving at the final photodiode, (b) shows the signal collected by the first photodiode, and (c) shows the original data from the final photodiode normalized using the data from the first one. – courtesy [4]

3. Upgrades

3.1 Stabilizing the optical board

When our SMOKE instrument was originally setup, the supports for the optical board were built out of wood and were unsecured to the rest of the system as a temporary solution until it was shown that the SMOKE worked. Once the SMOKE has been shown to work in the previously described configuration, we decided to take steps to make the system more stable and to increase functionality. The first step was to secure the optical board to the frame of the magnet. This is important for several reasons. The first is that it helps protect the optical components from potential damage should something bump into the instrument. The second is to ensure consistency between the measurements since moving the optical board would affect the incident angle of the beam on the sample.

The optical board was secured directly to the pre-existing frame of the electromagnet as shown in Figure 10, using hollow 1-inch aluminum tubing, aluminum bolts and aluminum standoffs. Aluminum tubing was used since it is lightweight and relatively inexpensive but is also sturdy and non-magnetic so that it will be unaffected by the field from the electromagnet. If it becomes necessary in the future to adjust the setup, the supports can be removed by unbolting them from the electromagnet's frame. The horizontal position of the table is limited by the available positions of pre-existing holes in the optical table, however the vertical position of the optical table relative to the electromagnet could be adjusted by using shorter or longer standoffs and aluminum bolts.

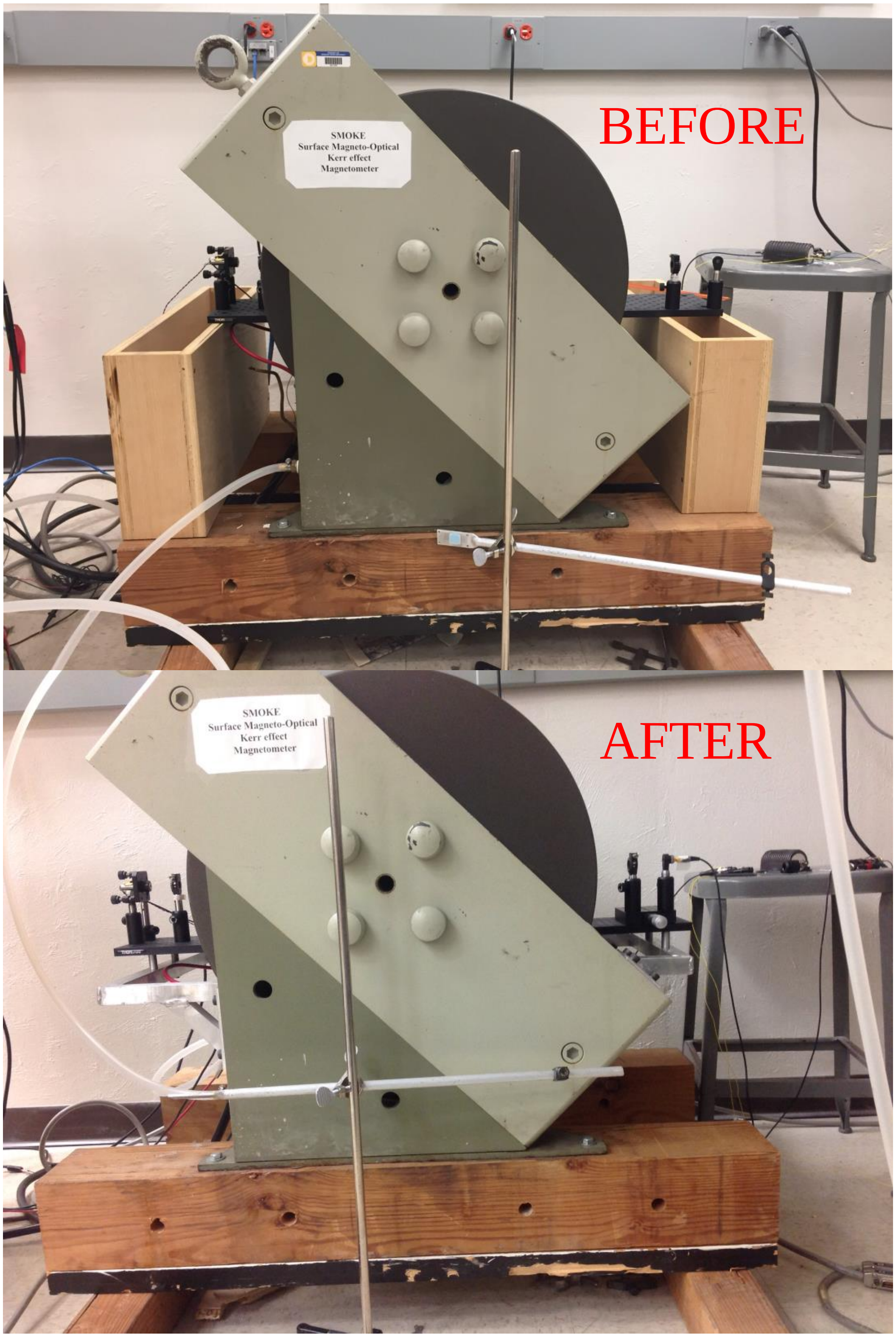

Figure 10 Before and after pictures of the supports for the optical table. The picture on the left shows the original supports made out of wood and unsecured to the aparatus while the picture on the right shows the upgraded aparatus with aluminum supports bolted directly to the aparatus.

3.2 Incident Angle translation

The second upgrade to the SMOKE's apparatus was to introduce the ability to change the incident angle of the beam on the sample. This is achieved using a moveable mount to adjust the position of the first mirror as shown in Figure 11. The subsequent mirrors are wide enough to still be able to reflect the beam despite the change in incident angle. The second polarizer and photodiode need to be moved simultaneously so to remain aligned with the beam while the incident and reflection angles are varied. This is achieved by using a dovetail translation stage as shown in Figure 12.

Figure 11 Picture showing a top view of the first mirror placed on a moveable mount to allow for incident angle adjustment.

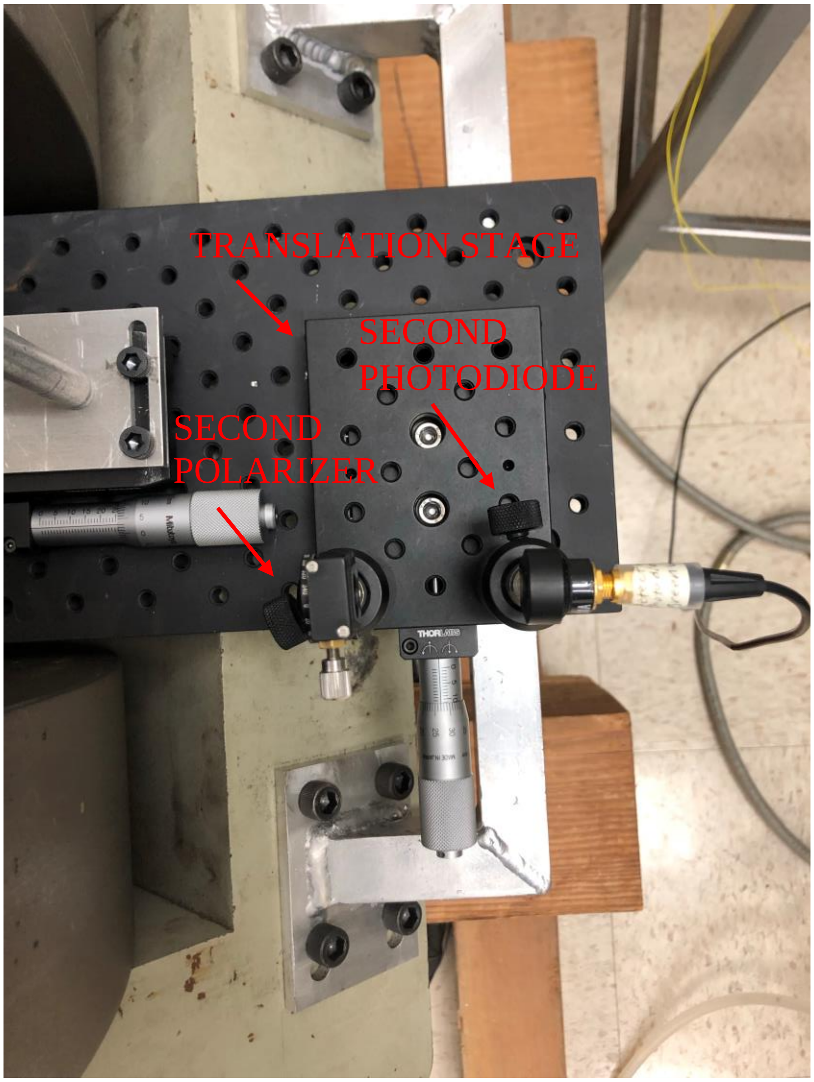

Figure 12 Picture showing the second polarizer and photodiode placed on a translation stage to allow them to be moved into the correct position to catch the beam.

While we have yet to study the effect of the incident angle on the SMOKE signal, we plan on doing this with the upgraded setup, and with the newly installed stage we should be able to do this more effectively.

3.3 Sample Translation

The last change we made to the instrumental setup of our SMOKE's apparatus was to include a mount to allow translation of our sample horizontally. This will allow us to study different portions of the same sample without the need to unmount and remount it. With wedge-shaped samples, different portions of the sample have different thicknesses. It is suspected that the thickness of the sample will affect the shape of the hysteresis loops and future studies will be done using the SMOKE to measure possible relationships. Since our samples are often fragile, having the ability to translate the sample with accuracy without having to continually unmount and remount it will make such a study safer, easier and more accurate.

The translation device is built out of ½ inch solid aluminum tubing, ¼ inch aluminum plates, 1-inch solid aluminum block and aluminum M6 cap screws. It is mounted on a compact dovetail translation stage. The slots in the baseplate of the translation stage allow for small adjustments perpendicular to the direction of travel of the translation stage to help align the mount plate as close to the magnetic pole as possible to save room. The device utilizes two vertical poles to increase the stability of the mount and to help keep the mount plate aligned along the direction of travel. The screws on the 90˚ brackets can be loosened to make major adjustments to the horizontal position of the mount plate along the direction of travel as well as adjustments to the vertical position of the mount plate. A CAD drawing of the mount is shown in Figure 13 as well as a picture of the actual mount in Figure 14.

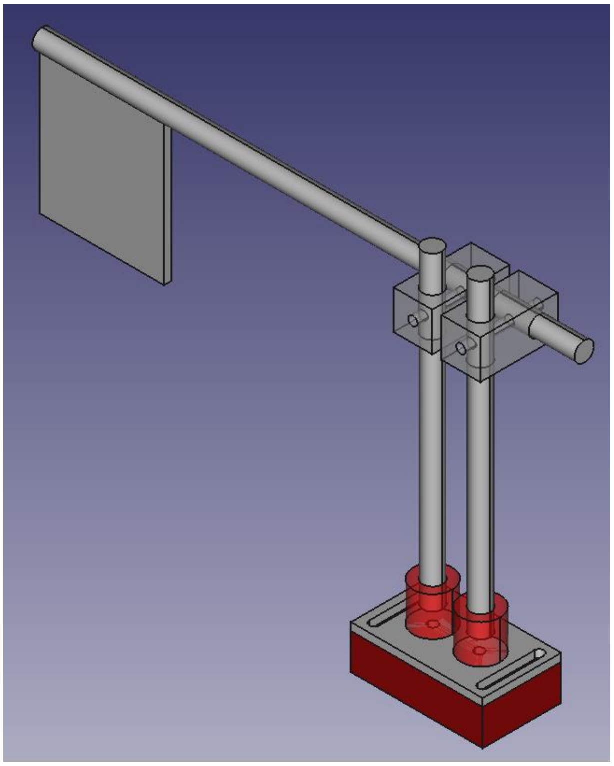

Figure 13 A CAD drawing of our sample mount showing the overall structure

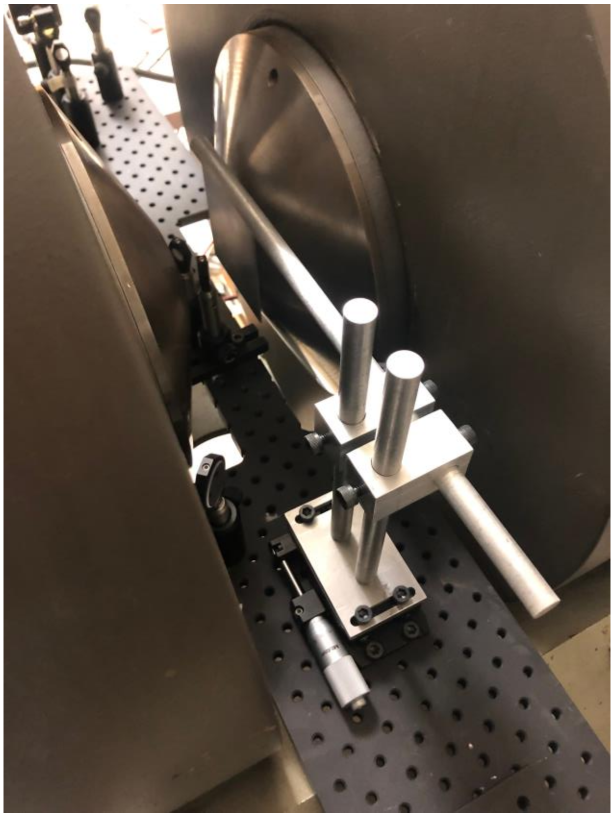

Figure 14 A picture of the actual translation device mounted on our system

4. Conclusion

The Surface Magneto-Optical Kerr Effect magnetometer is a powerful tool for acquiring hysteresis loops of ferromagnetic thin films. It does this by applying a varying external magnetic field and then using the Kerr effect to measure the internal magnetization of the sample. Replacing the temporary wooden supports with aluminum ones bolted directly to the frame has improved the stability of our instrument and will help protect the optics. Introducing the ability to change the incident angle of the laser beam on the sample has allowed studies on the effect of the incident angle on the SMOKE measurements. Finally, by introducing a translation mount for the sample holder we will be able to do an additional study of the effect of the thickness of our sample on the magnetic behavior of the material without the need to unmount and remount the sample, increasing the accuracy of the SMOKE measurements and protecting the sample.

We have had problems recently with the stability of the Master-Slave power supply setup that we use to power the electromagnet. We are currently working with the BYU physics department’s electrical shop to identify the source of the instability so that we can correct it and begin our next experiments.

References

[1] Sung, Hilda W. F. and Rudowicz, Czeslaw, “A closer look at the hysteresis loop for ferromagnets – A survey of misconceptions and misinterpretations in textbooks”. arXiv.org arXiv:cond-mat/0210657 (2002)

[2] Qiu, Z. Q. and Bader, S. D., “Surface magneto-optic Kerr effect”. Rev. of Sci. Instrum. 71:3, 1243-1254 (2000).

[3] Tapoan ik, Juraj and S. D. Steenwyk. “Surface Magneto-Optic Kerr Effect.” (2007).

[4] Sorensen, Susan Stoffer, “Development of a Surface Magneto-Optic Kerr Effect Magnetometer”. (2013)

[5] Kepco Power Solutions, Operator’s Manual BOP (M) (D) 100W, 200W, 400W Bipolar Operational Power Supply (2018). Retrieved from www.kepcopower.com/support/bop-operator-r8.pdf