Solving the Mystery of the H1 field

A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science degree in Physics from the College of William and Mary

by

Matthew Roberts

Advisor: Todd Averett

Senior Research Coordinator: Gina Hoatson

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Mentor: Todd Averett

Matt Roberts

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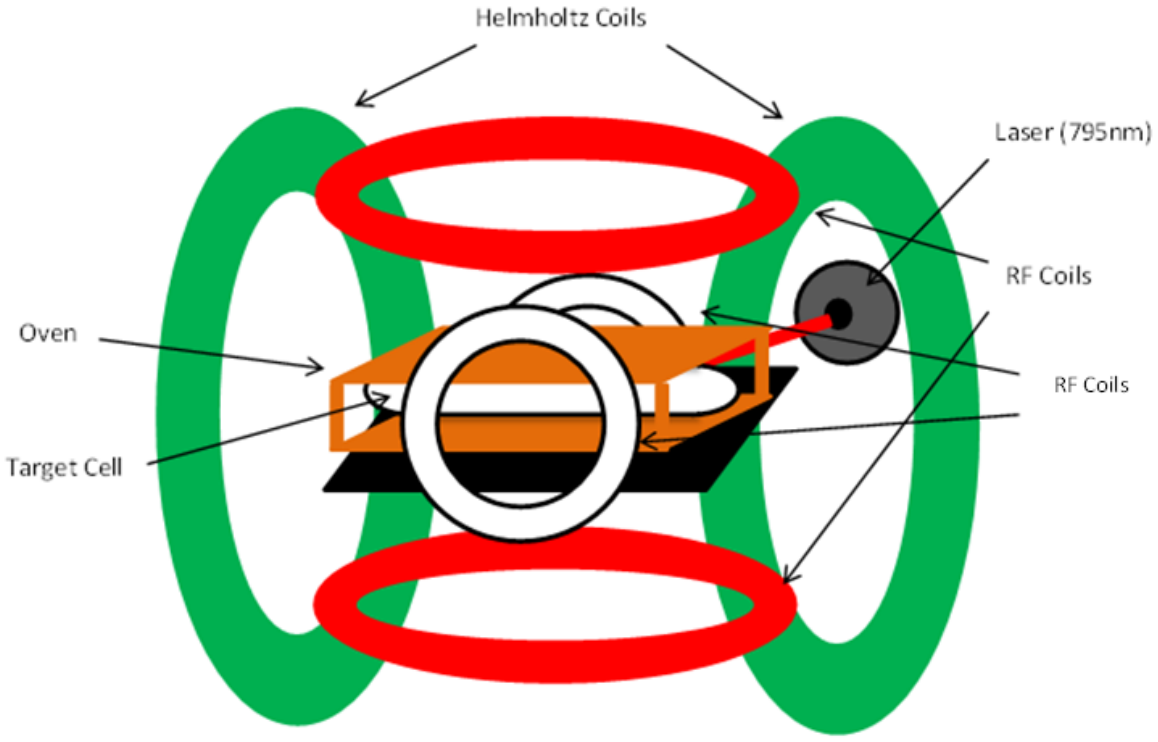
Abstract

This report discusses the progress in the investigation of the non-negligible difference between NMR signal peaks and widths of a polarized ^{3}He target cell in parallel and perpendicular orientation with respect to an external magnetic field. The solution to this issue is paramount to the polarization of future cells, since this problem may hinder accurate polarization, EPR, and NMR measurements. These polarized helium cells are used by Jefferson Lab in ongoing experiments concerning the structure of the neutron. This problem must be solved before the next cell is made. The polarization, and thus peak heights should not decrease due to switching the cell's orientation. This phenomenon was the start of this investigation, and various methods to attempt to understand the source of this problem were explored.

Introduction

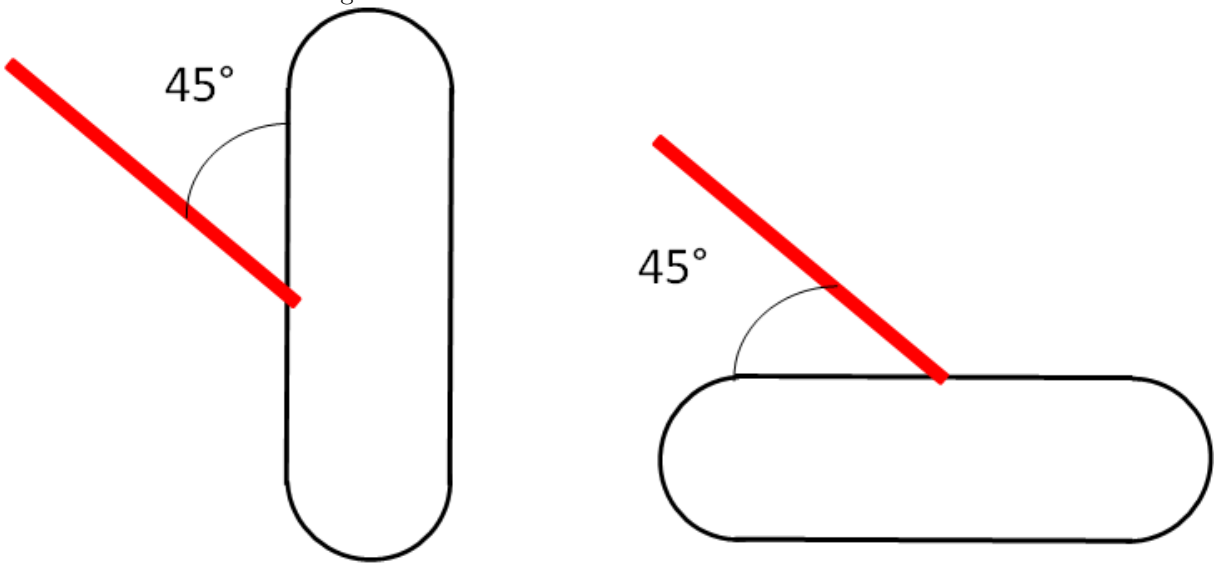
Figure 1: Apparatus used to polarize the cell



The green rings in the diagram above are Helmholtz coils designed to generate a constant, uniform magnetic field. The red and the white rings are the RF coils, which generate a time-varying, uniform magnetic field perpendicular to the field generated by the green coils. The orange box with the white tube in the center is the cell oven with a cell designed for the determination of the κ_0 constant. The apparatus used to polarize

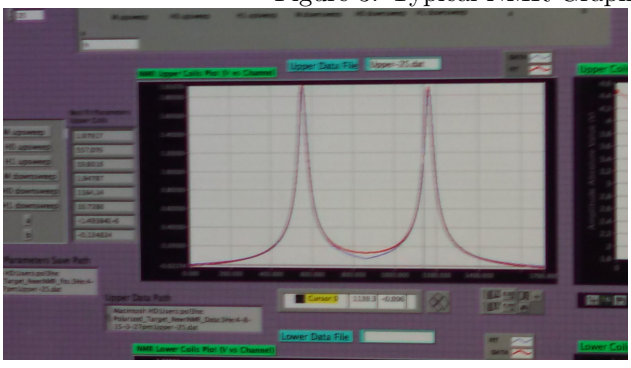
and study the cell consists of three Helmholtz coils mounted along three perpendicular axes. The cell oven used to heat the cell being studied can be put into two orientations, which we've called "parallel" and "perpendicular". Their names are based on their positions in relation to the green Helmholtz coils, either parallel to the field they produce or perpendicular to it. The cell is polarized using an infrared laser from a fiber optic cable and shines it light at a 45° angle to the RF coils, so that light comes in at the same angle to the cell in both orientations.

Figure 2: Laser in relation to both orientations



The left diagram illustrates the parallel orientation, while the one on the right illustrates the perpendicular orientation. After a cell has been filled and polarized, measurements can be taken to determine its polarization and alkali metal ratio. In Nuclear Magnetic Resonance (NMR), the spins are aligned in the field generated by the green coils, also known as the holding field, then they are "flipped" by the field generated by the white coils, also known as the RF field. and then flipped back to their original spin alignment. The data from those spin flips are recorded on computers.

Figure 3: Typical NMR Graph



(Source: T.D. Averett)

The data collected usually contains two peaks, the first located where resonance was achieved during the initial flip, and the second is located where resonance was achieved when the spins were flipped back. A best fit line on the data allows an estimation of important information such as the height of the peaks and their widths. To the left of the graph, are the best fit values for several variables. The ones we concern ourselves with the most are "M upsweep" and "M downsweep", the two peaks of the NMR graph. These peaks and widths help determine the polarization of the cell, and as more NMR measurements are taken, the depolarization or relaxation rates can be determined.

The H_0 field takes advantage of the Zeeman effect in an atom, which splits the energy levels between the spin-up and spin-down states of an electron at a certain energy level. Normally, this phenomenon is used to determine the absolute polarization of the helium through a process called Electron Paramagnetic Resonance (EPR). Since a polarized gas has its own magnetic field, it increases or decreases the net magnetic field of the holding field, H_0. In an atom with a non-zero spin value, there is a hyperfine splitting between energy levels, meaning that in a stronger magnetic field, more energy is needed to jump between these states. EPR takes advantage of this by measuring the energy of the photon that is emitted from a transition to a lower state. At this point, the spins are pointing either parallel or antiparallel to the holding field, making the net magnetic field $H_0 \pm M_{He}$. When the spins are flipped, and the spins are pointing in the opposite direction, and the magnetic field becomes $H_0 \mp M_{He}$, where M_{He} is the magnetic contribution from the polarized ^{3}He. With this new magnetic field, the energy gap between states changes, and thus the energy of the photon emitted in the same energy transition changes accordingly. When the difference between these energies is taken, we find that the holding field contribution is canceled out and we are left with the magnetic field contribution of the polarized gas. This, in turn, is proportional to the polarization of that gas.In the equation for determining the polarization of the cell, there is a constant known as κ_0. This constant is temperature dependent, and is different for each alkali isotope.

$$\Delta\nu_L = \frac{d\nu_{EPR}(F,M)}{dB}\mu_{He}n_{He}P_{He}(\frac{8\pi}{3}\kappa_0 + (4\pi - \frac{8\pi}{3})) \tag{1}$$

$$\Delta\nu_T = \frac{d\nu_{EPR}(F,M)}{dB}\mu_{He}n_{He}P_{He}(\frac{8\pi}{3}\kappa_0 + (2\pi - \frac{8\pi}{3})) \tag{2}$$

These equations are used with the cylindrical cell, since its geometrical design allows us to find the value of κ_0, where the subscript L corresponds to the longitudinal or the parallel orientation and the subscript T corresponds to the transverse or perpendicular orientation. The equation states that the difference in frequency (ν_{TorL}) is equal to the derivative of the frequency with respect to the magnetic field in a certain spin state($\frac{d\nu_{EPR}(F,M)}{dB}$), times the magnetic moment of helium (μ_{He}), times the amount of helium per unit

volume (n_{He}), times the polarization (P_{He}), times a geometrical term. For his Senior Thesis, Nick Penthorn attempted to measure this constant for several alkali isotopes. The values he obtained from his tests were different from the values established in a paper done by physicists at Princeton back in 1998. However, recently a peculiar effect occurred when measurements were taken in different cell orientations. When a measurement was taken in one orientation, and then switched to the other, there was a significant decrease in the cell's polarization. However, when a second measurement was taken in the cell's original orientation, the polarization appears to have returned to its original level of polarization. This should not happen, as simply rotating the cell should not affect its polarization, and the time it takes to do so is much less than the cell's normal relaxation time. But, most importantly, the polarization should definitely not increase from rotating the cell back to its original configuration. This problem made us wonder whether this polarization difference affected the previous measurements. After this problem is solved, we plan to recreate Nick's tests and check to see if our measurements agree with his. The cause of this problem has been studied for the past few months, and several techniques have been employed to root it out.

Theory

The target cells are made with a glass known as alumiosilicate, which is used because the depolarization of the helium is minimized with this material. In a process that takes about a week, the cell is filled with ^{3}He, N_2 (which is used to help with the polarization), and an alkali metal vapor (potassium and/or rubidium). When the cell is ready, it is placed into an oven designed to keep the cell at 180°C for a cell with only rubidium, and 230°C for a potassium-rubidium hybrid cell, in between two sets of Helmholtz coils. A circularly polarized laser is pointed at the cell, and begins the polarization process. This laser polarizes the helium through a process known as Spin-Exchange Optical Pumping (SEOP). The laser has a wavelength of approximately 795 nm, which is used to excite the single valence electron of the Rb atoms in the alkali vapor. When the electron returns to its ground state, it will be in two possible spin states. If it is in the spin down state, then it will become excited by the laser again, and repeat the process all over again. However, if it is in the spin up state, then it will remain in that state even if the alkali comes into contact with the laser again, due to the selection rule of angular momentum which forbids the transition from the spin up ground state level to the first excited state. While the alkali is in vapor form, it will collide with helium atoms, and when that occurs, they will "trade" spins, leaving helium nuclei with the desired spin state, and the alkali can be polarized by the laser. In the lab, we refer to the polarizing and depolarizing the cell as "spin up" and "spin down"processes, respectively. During spin up, we set the oven temperature to the appropriate temperature, and turn the laser on. The rate at which the cell is polarized is determined by several factors.

It is determined by the following equation:

$$\frac{dP(t)}{dt} = (1 - P(t))\gamma_{SE} - P(t)(\Gamma_r + \gamma_{SE}) \tag{3}$$

This equation states that the rate at which the spins become polarized($\frac{dP(t)}{dt}$), depends on the polarization of the cell at that time (P(t)), the rate of spin exchange between potassium and helium-3 (γ_{SE}), and the relaxation rate (Γ_r). The first half of the term(the terms to the left of the minus sign) is the part that contributes to the polarization, while the second half(the terms to the right of the minus sign) is the part that destroys the polarization of the cell. It is important to note that the same exchange rate that is important in the polarization process, also contributes to the destruction of that polarization, since polarized helium atoms and unpolarized alkali atoms can collide, leaving the helium with an undesired spin state. When this equation is solved for P(t), we get

$$P(t) = P_{Max}(1 - e^{\frac{-t(\Gamma_r + \gamma_{SE})}{\gamma_{SE}}}) \tag{4}$$

This suggests that due to the depolarization term of the polarization rate equation, the polarization can only reach a maximum value, P_{Max}. The plot for this equation has an exponential form, but stops increasing at P_{Max}. For spin down, the lasers and the oven are turned off, allowing the alkali to condense back to a solid form. The spin down process is far simplier in terms of the math, since the polarization rate takes the form

$$\frac{dP(t)}{dt} = -P(t)(\Gamma_r) \tag{5}$$

and the polarization at time t is

$$P(t) = P_0 e^{-t\Gamma_r} \tag{6}$$

where P_0 is the polarization of the cell right after the laser is turned off. After the cell has been polarized by the laser for several hours, the RF Helmholtz coils are turned on. The green coils generate a constant, uniform magnetic field between them that we refer to as the H_0 field. This field is always kept on in order to polarize the cell. Inside the space between those coils are the RF coils, which generate a magnetic field that changes with time, known as the H_1 field. In the current experimental setup, we use the white RF coils to generate the H_1 field. The method we use is known as NMR Adiabatic Fast Passage (AFP). This H_1 field is extremely important in AFP because that field strength dictates the parameters of AFP. The equation for these parameters are

$$\frac{H_1}{T_R} \ll \frac{dH_0}{dt} \ll \gamma_{He} H_1^2 \tag{7}$$

where T_R is the relaxation time, $\frac{dH_0}{dt}$ is the rate at which the magnetic field is changing, also known as the sweep rate, and γ_{He} is the gyromagnetic ratio of helium. These spins must be flipped at a rate that is much faster than the relaxation time of the cell, but much slower than the frequency at which the spins precess (the Larmor Frequency). If these conditions are not met, measurements will be inaccurate, and the cell's relative polarization cannot be determined. We can determine the relaxation time through a test involving a series of NMR and EPR measurements, and plotting the data to find its value. However, due to the polarization issue, we cannot be sure that the results of this procedure are accurate. We made a plan to find this problem, by starting with a dummy check on the magnetic flux through a loop of wire, checking the equipment for any malfunctions, checking on whether the root mean square current (I_{rms})in the RF coils was properly saturated, and mapping the H_1 field with a loop of wire.

Matlab Code

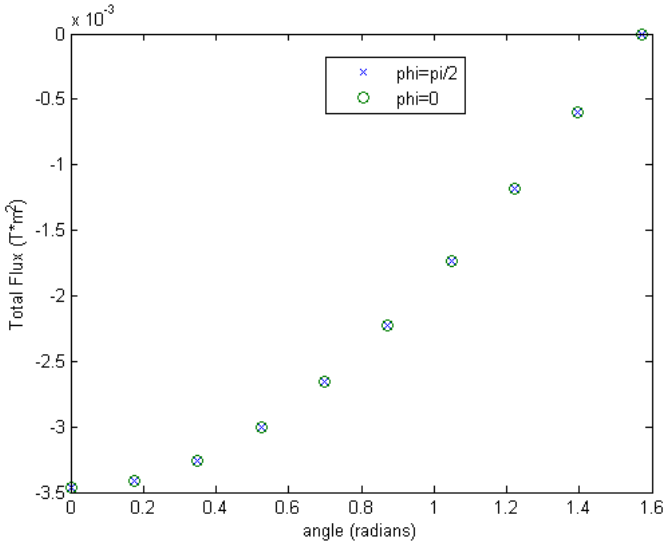
Experiment

The first step we took was a numerical check on whether the magnetic flux through a rectangular loop of wire changed if the cell was rotated from one orientation to the other. This simulates the cell in its two different orientations, parallel and perpendicular. To simulate this, we placed a single dipole outside of the loop of wire and made it point in one of two different directions, one where ϕ (the direction of precession)=0°, and the other was where $\phi = 90°$. The purpose of this was to simulate when the cell was in the parallel and perpendicular orientations. The code works by treating each of the spins as a magnetic dipole. It treats the dipole as though it were stationary and finds the distance between the dipole and several points on the coil of wire. The code separates each side of the coil into smaller segments and calculates $\vec{A} \cdot d\vec{l}$ for that segment, where $\vec{A}$ is the magnetic vector potential, and $d\vec{l}$ is the length of the small segment of wire. Since the formula for the magnetic vector potential of a dipole is typically given in spherical coordinates, we made it easier on ourselves by converting it to rectangular coordinates. The code follows the wire, then moves on to the next side when it reaches the end of one side. Then, the code adds all of those values together to give the total magnetic flux for the loop. A code was written for each ϕ value, each exactly the same as the other, except with the appropriate values of ϕ plugged in, and a third code was written to compare the magnetic flux values of the two orientations for different polarization directions (designated by θ). The values of the flux were taken in 10° increments, and a graph is then created to plot these values against the other orientation to find any noticeable difference in their flux. All three codes used in this test have been included, along with comments explaining how it works, and can be viewed in the Appendix.

Results

After numerous attempts (and a few failures on my part to code it properly), I successfully created a code to simulate the magnetic flux through a coil of wire. The results were very encouraging, since we found that the magnetic flux through the coil should not matter in which direction the spins are precessing.

Figure 4: The Flux Graph



In this graph, we have defined $\theta = 0°$ as when the spins are pointing in the direction perpendicular to the plane of the coil. Likewise, we have defined $\theta = 90°$ as when the spins are pointing in the direction parallel to the plane of the coil. As expected, the highest magnitude of the flux occurs when $\theta = 0°$, and goes to zero when $\theta = 90°$. There is obviously no difference between when the cell is in the parallel orientation ($\phi = 0°$) and when the cell is in the perpendicular orientation ($\phi = 90°$). After this important result, we moved on to the saturation curves and possible hardware issues.

Equipment checks and the Saturation Curves

Experiment

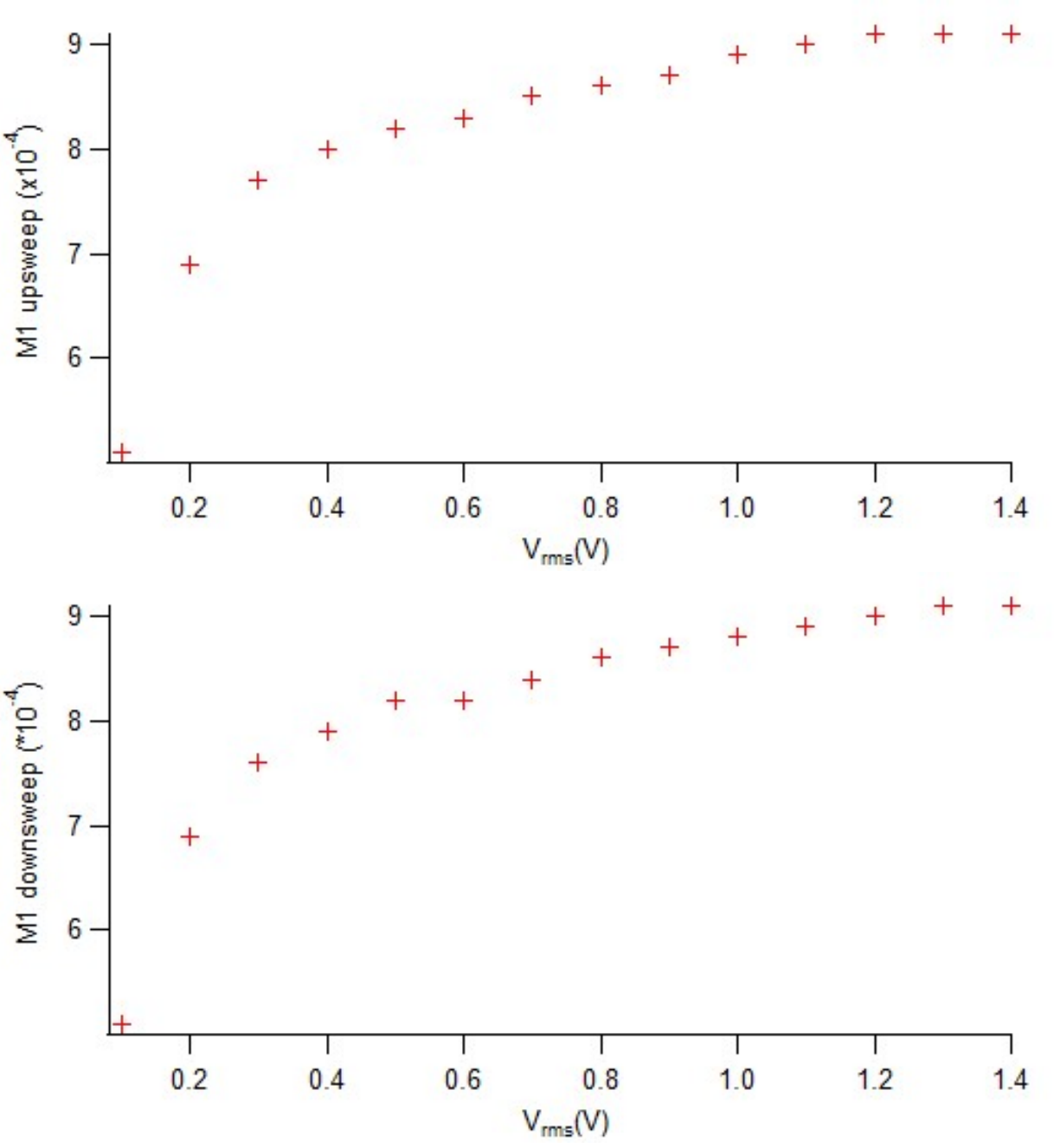
The next step in our investigation was to investigate the possibility of an important piece of equipment malfunctioning. We checked the spectra of the lasers to see if they were producing the correct wavelength, checked that the oven was maintained at the correct temperature (210°C), and that all wires were in the correct inputs and outputs. Afterwards, we checked if the I_{rms} was beyond the saturation point. When the current is within the saturation range, it means that no matter what current is run through the RF coils, the

peak height of the NMR signal will remain the same. I_{rms} is the current used to generate a magnetic field in the RF coils. If it wasn't, then the conditions of AFP will not have been met, and may explain this strange phenomenon. To test this, we placed a test cell in the apparatus, and recorded the values for the signal peaks, H_1, and I_{rms}. Since the value of I_{rms} determines H_1, we know that when the values for the signal peaks remain relatively constant, then the voltage is beyond the saturation point and the value of H_1 meets the requirements for AFP to work. A low voltage well below the estimated saturated point (such as $0.1V$)is chosen as the starting point, and the voltage is increased by a set amount after each set of measurements, recording the signal peaks, H_1, and I_{rms}. The signal peaks and H_1 have two sets of values, one for the initial flip, or the "upsweep", and the other for the flip back, or the "downsweep". These points are then graphed together and the saturation point can be identified visibly. These graphs are often referred to as "Ioannis Curves" and are often used to check if an experimental apparatus is within the AFP conditions. The initial sweep rate was $3\frac{G}{s}$, but in recent experiments, we have reduced that rate to $1.2\frac{G}{s}$.

Equipment Checks and the Saturation Curves

Initially, we had set the V_{rms} value to 1.0V, but we were unsure if this was well within the saturation range. When the voltage is within the saturation range, that means that any voltage within that range will give the same value for the upsweep peak at a given level of polarization. For our initial curve, we took fourteen points of data, starting with 0.1V and ending with 1.4V in 0.1V increments.

Figure 5: Initial Ioannis Curves



In these graphs, M1 signifies the magnitude of the NMR signal peak. As seen in the graphs, the 1.0V value seems to be on the threshold of saturation, however since we felt that 1.0V was a bit high for a threshold voltage, we decided to investigate into the possibility of a hardware malfunction. We were only comfortable with the RF signal generator outputting a maximum of 1.4 V, so we checked if the lasers were giving off the appropriate power and wavelength of light. We found that the polarizing laser wasn't working properly, but that problem was quickly rectified. We tried the Ioannis curves again, and we saw large difference from the

previous trials.

Figure 6: Ioannis Curves at 3 G/s(V_{rms} values)

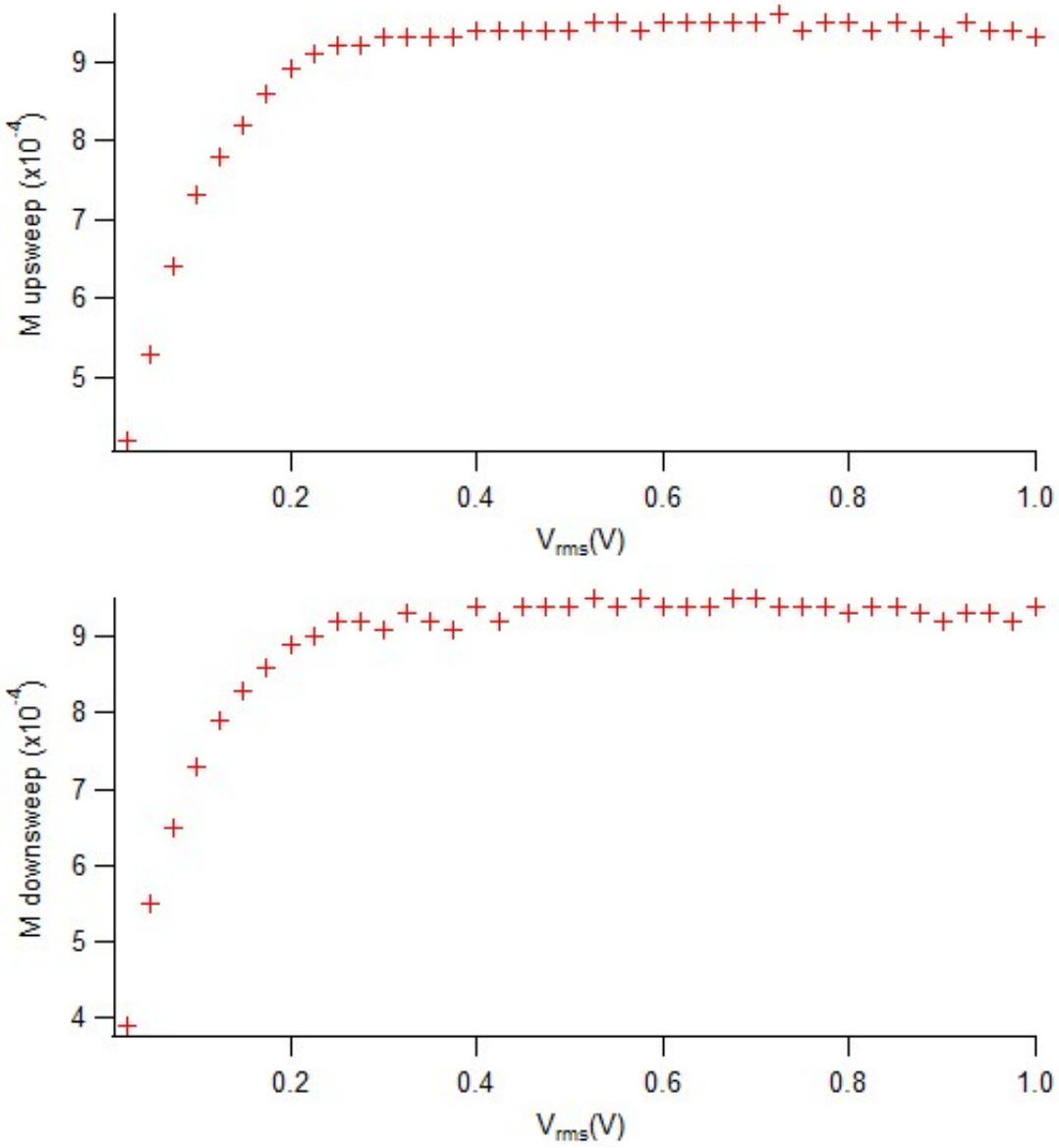
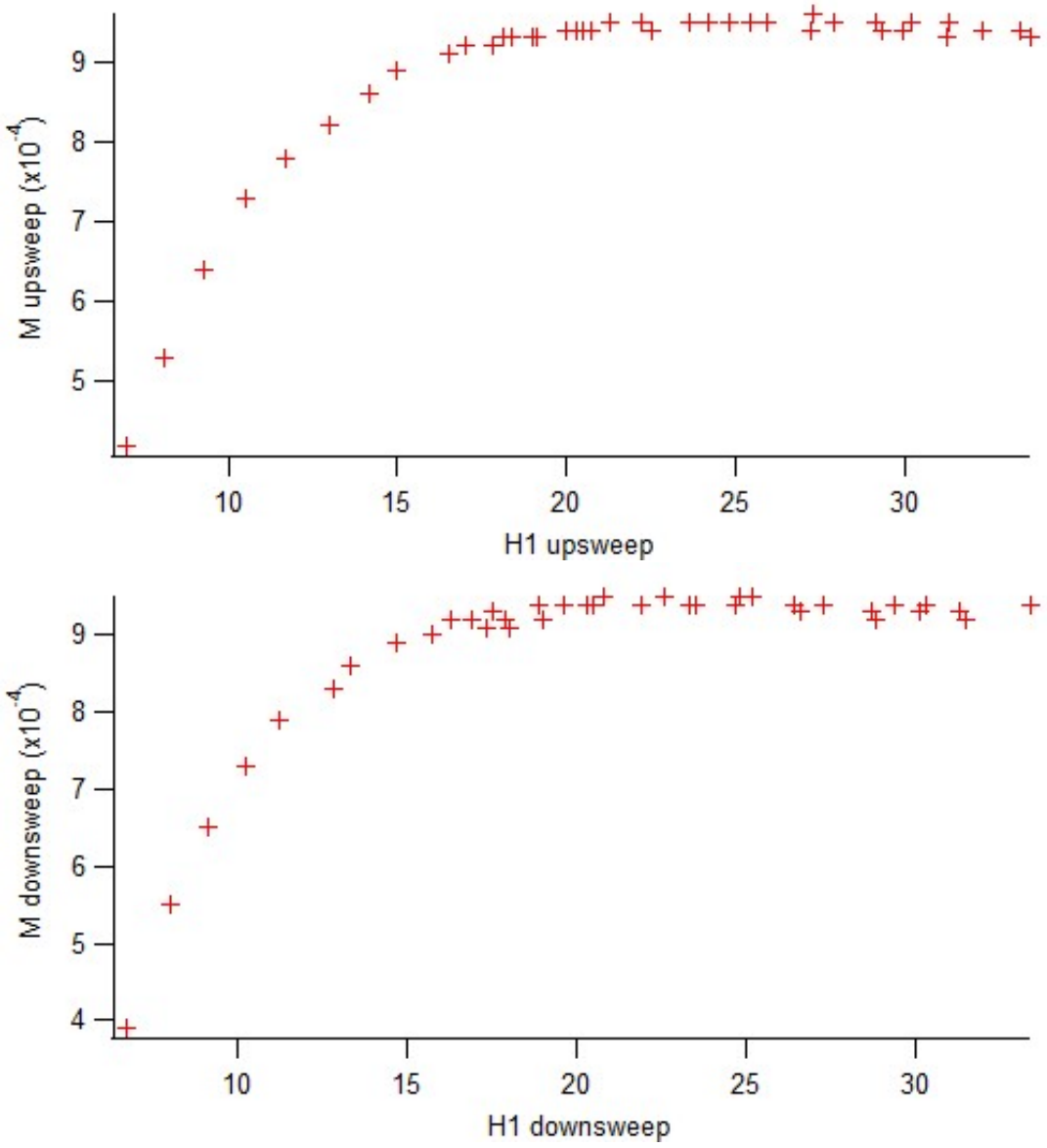


Figure 7: Ioannis Curves at 3 G/s(H_1 values)



It was very different because the threshold voltage was found to be a lot lower, much to our joy. We have attempted a third trial of Ioannis curves for a sweep rate of $1.2\frac{G}{s}$, but when we attempted to take our measurements, we found that the first value for V_{rms} was so low that it wasn't flipping enough spins. Due to this unfortunate circumstance, the accompanying NMR destroyed the polarization of the cell and we were unable to take reliable measurements.

Mapping the H_1 field

Experiment

Our final test involved the physical mapping of the H_1 field created by the existing NMR coils with a small pickup coil (wire wrapped around a small section of pipe) to see if the field was truly uniform. The changing magnetic field induced a voltage in this small coil, so we could measure the magnitude of the magnetic field at certain points between the coils as a voltage. To simulate the cell, we measured the center of the cell in the oven to the surface where it rested, and found a book thick enough such that when the small coil rested on it, the center of that coil was at the same height as the center of the cell. While the coil rested on top of the book, the voltage was mapped in a 1 ft^2 area centered in the middle of the NMR coils, and each measurement was taken in 2 inch increments, for a total of 49 measurements.

Results

After all of the points were recorded, we found the results to be encouraging. The voltages recorded are peak to peak, and measured in volts. In the following graph, we define the x-axis as parallel to the direction of the field generated, and the y-axis as perpendicular to the field. The point $(0, 0)$ is defined as the center of the field, equidistant from the coils in inches.

Table 1: V_{rms}(in volts) values at different postions within the H_1 field

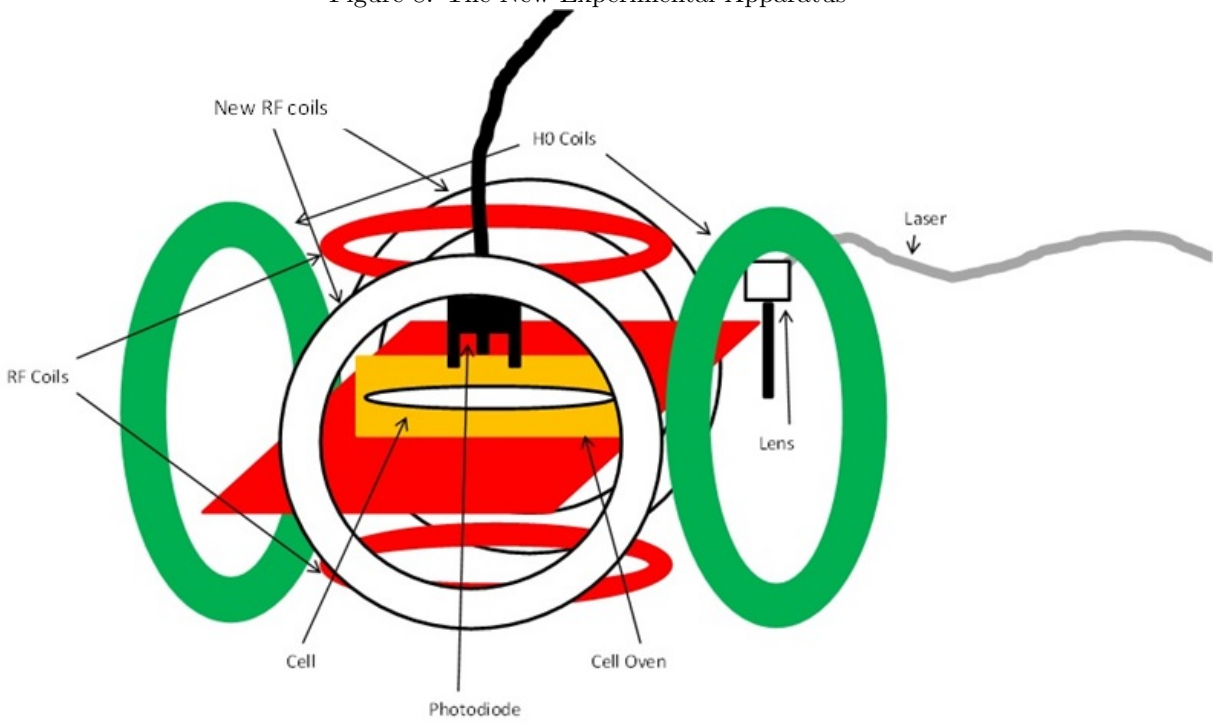
Positions(inches)	-6	-4	-2	0	2	4	6
-6	0.910	1.68	2.20	2.44	2.44	1.96	0.704
-4	0.890	1.19	1.45	1.57	1.65	1.16	0.624
-2	0.860	1.02	1.25	1.32	1.21	0.910	0.608
0	0.810	0.970	1.10	1.16	1.08	0.870	0.568
2	0.880	1.08	1.23	1.32	1.18	0.900	0.620
4	1.10	1.53	1.63	1.76	1.56	1.10	0.808
6	1.40	2.12	2.44	2.52	2.48	1.86	0.872

The field appears to be strongest at the coils, and weakest at points directly to the left or right of the coils. The magnitude of the field is a sort of saddle, with the center as the saddle point. Since this field is not uniform as it ought to be, we have come up with a solution to rectify this. The field is the most uniform when the distance between the coils is equal to their radii, so we have measured the distance between them, and found the distance to be 21 inches. The radii of the NMR coils are nowhere near that, so we had new coils made that fit this condition in the machine shop.

Part Two

The new coils were made and attached to the apparatus at the beginning of the spring semester, and wound with four turns of copper wire each. The coils have a radius of approximately 53.5 centimeters, satisfying the condition for Helmholtz coil field uniformity. Terminal blocks were drilled onto the acrylic frame of the coils where the extra length of copper wire was mounted, connecting them together.

Figure 8: The New Experimental Apparatus

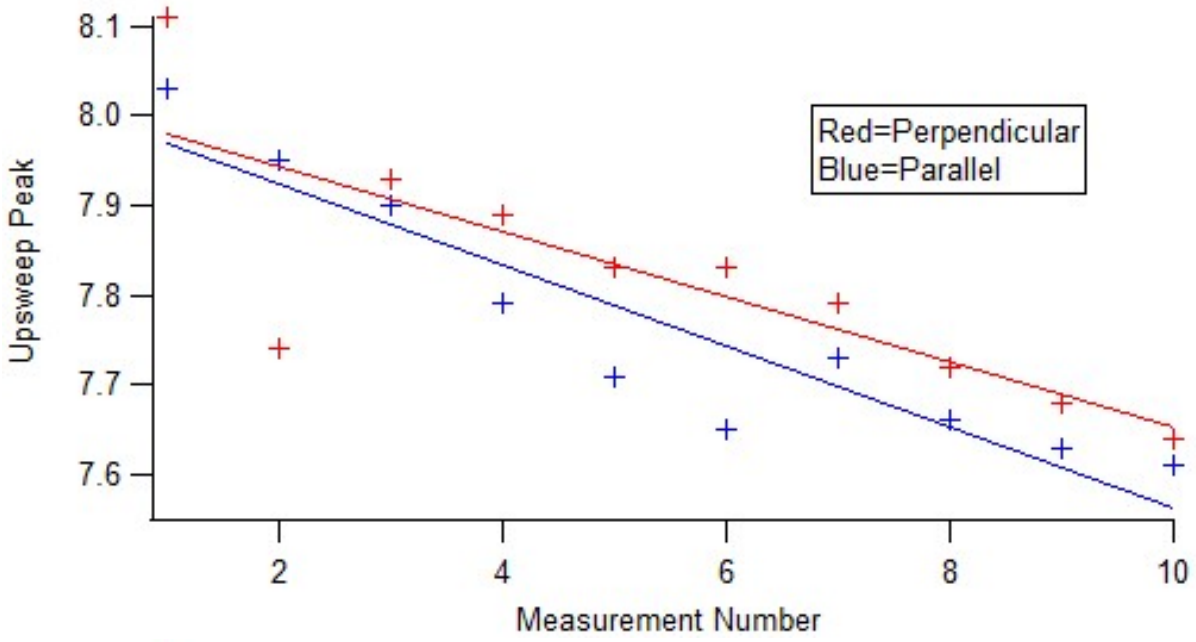


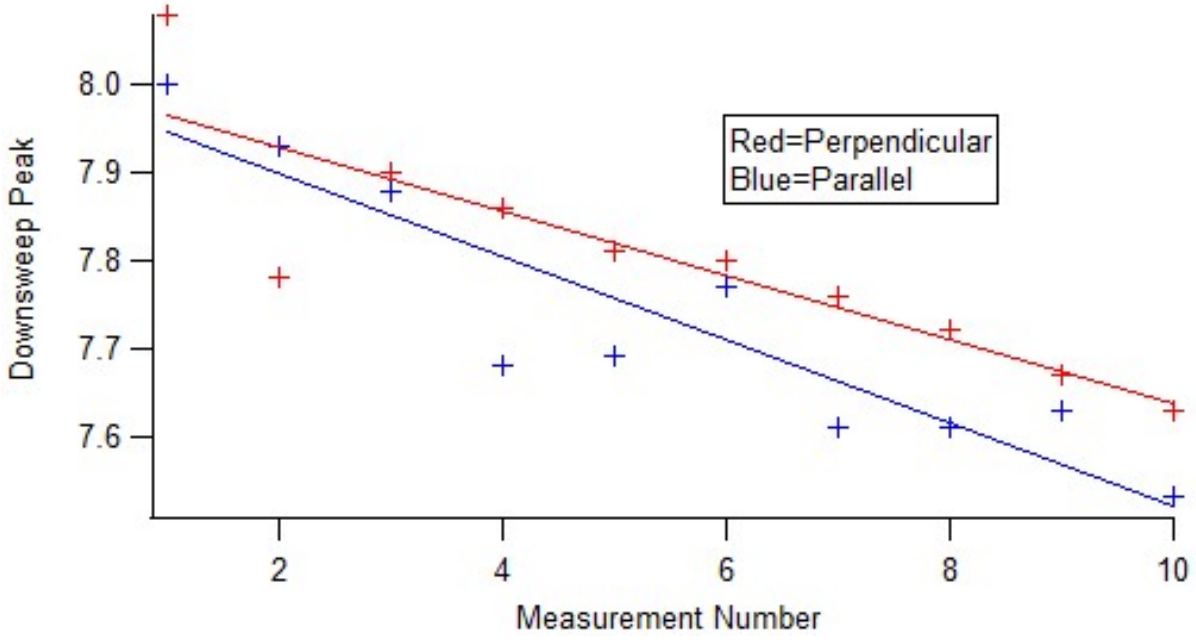
After we made sure the coils were wired correctly, we used a small pickup coil to test the field's uniformity. When we moved the coil in different positions between the new coils, we found no noticeable gradient in the field's strength.

Orientation Polarization Test

With the new coils in place, we needed to see if the apparent orientation difference in the polarization was still there. With the cell in place, we performed NMR, rotated the cell, and repeated the process. We continued to do this until we got ten measurements for the parallel and perpendicular orientations. When all of the data was collected, we plotted of the parallel measurements together with one best fit line, and all of the perpendicular measurements together with another best fit line.

Figure 9: Signal Peaks vs. Measurement Graphs





The parameters for the four best fit lines are as follows. The upsweep perpendicular measurements were found to have a slope of -0.036 ± 0.0096 and an intercept of 8.0 ± 0.060, the upsweep parallel measurements were found to have a slope of -0.045 ± 0.0062 and an intercept of 8.0 ± 0.039, the downsweep perpendicular measurements have a slope of -0.037 ± 0.0074 and an intercept of 8.0 ± 0.046, and the downsweep parallel measurements have a slope of -0.047 ± 0.0073 and an intercept of 8.0 ± 0.045. The slope in these graphs represent the depolarization of the cell over time, and the intercepts represent the original polarization of the

cell before the tests were done. We were very happy with these results since the intercepts agreed very nicely for both sets of upsweep and downsweep measurements, and the slopes were within one standard deviation of each other. With these results, we were able to conclude that the polarization discrepancy was resolved.

New Goals and New Problems

With the polarization issue resolved, we decided to revisit some old data to see if that was affected by the old NMR coils. Those coils were set up around the time another student, Nick Penthorn, was collecting data for his Honors Thesis. Nick took extensive data to measure the value of κ_0 and its temperature dependence for a few alkali isotopes. However, because of these problems, we cannot be certain of the accuracy of his measurements. We plan to follow his procedure in order to collect the data to determine κ_0, then compare our results.

EPR Problems

With NMR working perfectly, we decided it was time to measure the polarization with EPR. EPR, as stated previously, determines the absolute polarization by taking advantage of the hyperfine transitions between the energy states. When an EPR measurement is taken, all of the spins are "flipped", meaning that they are shifted to the opposite spin state at that energy level. They are then flipped back to their original spin state, and measurements in the difference in frequency is recorded. The data is collected by a photodiode, which then runs the data through a PI (Proportional-Integration) circuit. The purpose of this circuit is to lock on to a certain frequency that is associated with a transition of an alkali isotope. When there is too much noise, there are two knobs that control the relative and absolute gain of this PI feedback circuit, as well as the ability to change the phase of this circuit. The phase controls the output signal so that the signal we want to study is in one channel and the noise is separated into another channel. To check that the noise is being properly filtered, we run the program for EPR in scan mode and simply watch the line. This line is a measurement of the voltage (in microvolts) as a function of time. Ideally, we would like the line to remain at 0 microvolts so there is no offset in the measurements, and not fluctuate, but when this is not the case, the gain and the phase can be adjusted to remedy this. Often, we do not change the phase when this problem occurs, since once we have found a phase that completely isolates the signal from the noise, we do not change it. Typically, we like to keep the relative gain high, and the absolute gain low, since that is where we see the best results in our EPR readings. However, no matter how much we change the relative or absolute gain, we cannot minimize the noise to an acceptable level. Another, more irritating problem is

the fact that the feedback circuit seems to lock on to the wrong frequency. When we do get a measurement, the polarization is usually a single digit percentage. This unsatisfactory polarization can be attributed to two different scenarios: the polarization is actually very low, or the EPR feedback circuit is not working properly. The first scenario was explored briefly, and the lasers used for polarization have been known to sometimes malfunction.We decided to explore the second scenario, the faulty feedback circuit, more fully.

Building a better PI Feedback circuit

The current feedback circuit used in EPR has been in use for many years, and follows the textbook example of a PI circuit, but with knobs to adjust the gain of the proportional (P) and the integral (I) contributions. One of the biggest flaws with this circuit that we have is that in its current configuration, the absolute gain seems to be coupled with the relative gain, meaning that when we adjust the relative gain, the absolute gain must be changed as well. We plan to replace this circuit with one containing a programmable mbed micro controller.

Figure 10: Feedback Circuit Diagram

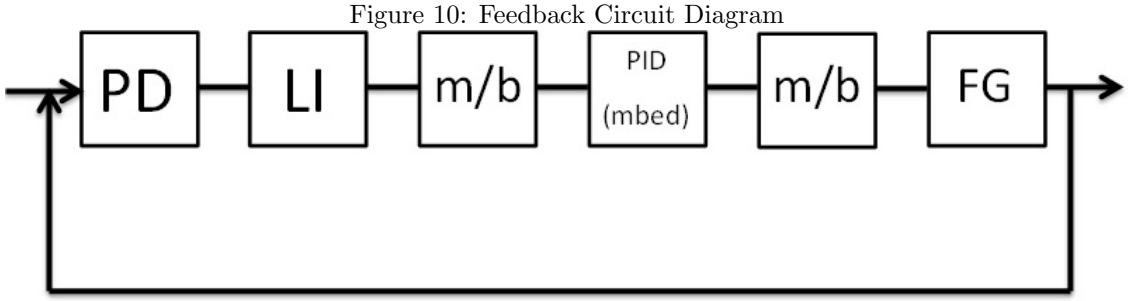
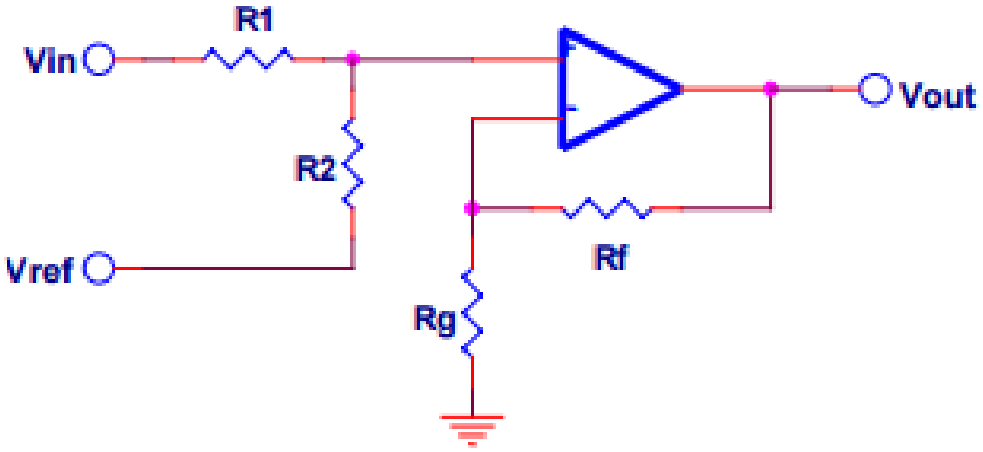


Figure 10 shows a block diagram of the different sections of the new feedback circuit. The light from the hyperfine transitions are picked up by the photodiode (PD), and that signal is magnified by the lock-in amplifier (LI). These components were already there, and remain unchanged. The new parts consist of the two gain and offset adjusters (m/b), and the new PID circuit controlled by the mbed (the micro controller). Any difference between the frequency of the RF coils and the frequency generator is detected and is adjusted accordingly. This new frequency is sent to the RF coils and its frequency is adjusted. This loop continues to adjust that frequency throughout the EPR process to stay on the frequency of the hyperfine transition. The gain and offset adjusters are simple op-amp circuits designed to translate the voltages between the signal and the mbed, and between the mbed and the frequency generator. Since the lock-in amplifier, the mbed, and the function generator run in different voltage ranges, these gain-offset adjusters are designed to "translate" voltages into values that can be read by the following component. To keep everything compact, we used an OP11, a component that has four separate op-amps. The first adjuster looks like

Figure 11: First Gain and Offset Adjuster



(Source:Carter 2002)

The purpose of this circuit is to change a -10 to 10 volt range to a 0 to 3.3 volt range. The gain, m, is found by dividing the difference between the output voltage range and the difference between the input voltage range. The offset, b, is found by the formula

$$b = V_{outZS} - m * V_{inZS} \tag{8}$$

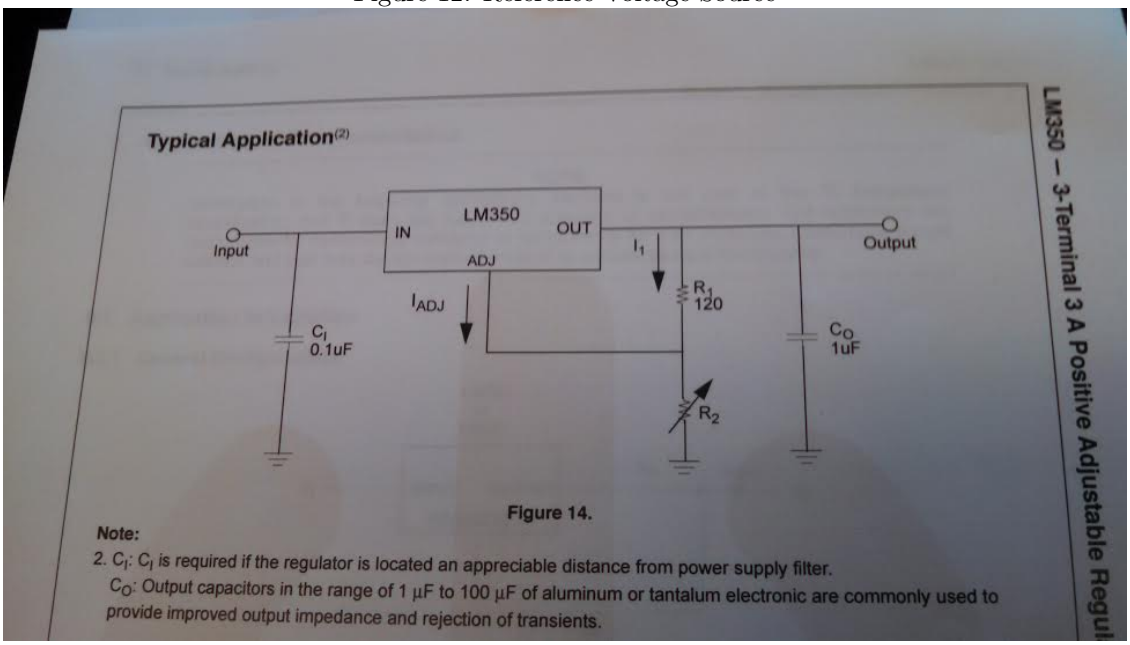
where V_{outZS} is the lowest output voltage (0V) and V_{inZS} is the lowest input voltage (-10V). The resistors R1 and Rf can be chosen to be as high or as low as we want. However, the resistors R2 and Rg are ruled by the formulas

$$R2 = \frac{V_{ref} * R1 * m}{b} \tag{9}$$

$$Rg = \frac{R2 * Rf}{m * (R1 + R2) - R2} \tag{10}$$

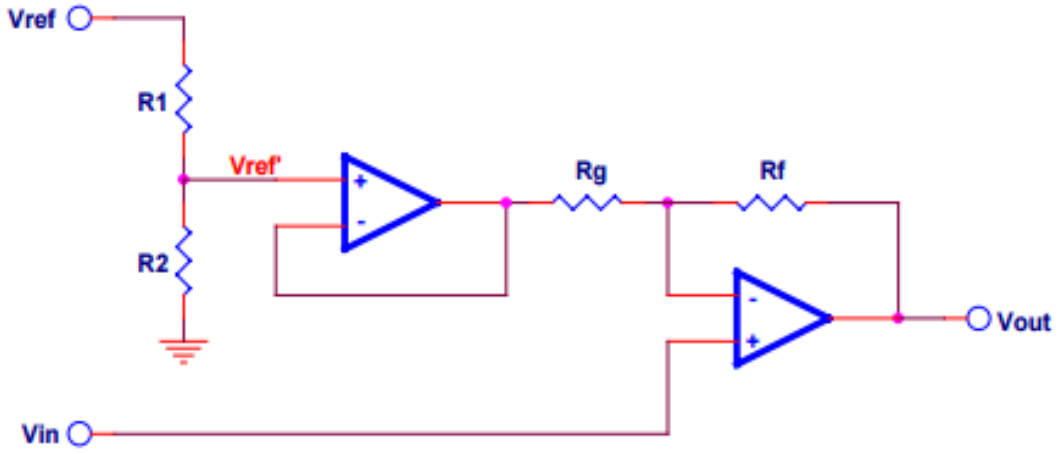
where V_{ref} is an arbitrary reference voltage. For Rg, we used a potentiometer, so that we can adjust the gain of this circuit whenever we need to. This reference voltage is provided by circuit with an LM350 semiconductor. This semiconductor can provide a steady output voltage between 1.2 and 33 volts when used in the following circuit:

Figure 12: Reference Voltage Source



This circuit is connected to a 15 volt power source, and R1 and R2 were chosen so that the output voltage was 1.23 volts. When everything is connected, the output of the first gain-offset circuit is fed to one the input pins of the micro controller. The micro controller is powered by a constant 5 volts provided by another simple circuit. This circuit is dictated by an LM7805 semiconductor, but all we did was to connect the 15 volt power source to its input and its output to the micro controller, providing a constant 5 volts. For the second gain-offset circuit, we used the following circuit:

Figure 13: Second Gain-Offset Circuit



For our reference voltage, we just used the 5 volt source powering the micro controller. Like the previous circuit, we had the liberty to choose our values for R1 and Rf. However, there is a formula to choose R2,

but we chose to ignore it due to the fact that it didn't give us the $V_{ref'}$ that we wanted, we chose a resistor value that achieved that desired value. For Rg, we used a potentiometer to adjust this circuit's gain as well.

Currently, the code on the micro controller is not complete, but I have included the code as it is right now in the Appendix. We are currently testing the output range from the lock-in amplifier, to see if its output voltage range is truly between -10 and 10 volts. So far, we see that it is not the case, and plan to adjust our circuit so that it can take a voltage range between -14 and 14 volts. The tests to see if our new circuit is a better fit for the EPR system will be carried out in the following weeks.

Conclusions

We have come across a multitude of problems in our quest to remeasure the value of κ_0, but despite the delays, we can say that unless another problem gets in our way, we should be able to start measuring its value during the summer. Our new NMR coils work beautifully, and should not give us any trouble in the foreseeable future. The rest of the semester will be dedicated to getting this new PI circuit up, running, and free of bugs, so that we can tweak our settings with better precision to get our strongest signals from EPR. Once we start testing κ_0, we will finally be able to see if the last results were skewed at all by the old NMR coils, and maybe get a better precision with some of the other parameters that had too large an uncertainty.

References

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[2] N. Penthorn, Honors Thesis, College of William and Mary (2014)

[3] J. Hill, "Construction and Characterization of Spin-Polarized ^{3}He Targets" (Research Experience for Undergradates, Williamsburg, VA, 2012).

[4] T.Averett, Notes and personal conversations, College of William and Mary (2014)

[5] Carter, B 2002, *Designing Gain and Offset in Thirty Seconds,* Texas Instruments, accessed 14 April 2015, http://www.ti.com/lit/an/sloa097/sloa097.pdf

[6]Fairchild Semiconductors 2014, *LM-350 3-Terminal 3 A Positive Adjustable Regulator,* Fairchild Semiconductors, accessed 14 April 2015, https://www.fairchildsemi.com/datasheets/LM/LM350.pdf

[7] M.V. Romalis, "Laser Polarized 3He Target Used for a Precision Measurement of the Neutron Spin Structure" (Stanford Linear Accelerator Center, Stanford, CA, 1997)

Appendix

Matlab Code with comments

Code for finding flux of dipole precessing about the x-axis. The coil is centered at (0,0,0), and the integral follows along the sides of the coil. The code finds the x,y, and z components of the distance between the dipole and the infintesimal length of a wire and uses that information to find the magnetic vector potential of that small section of wire.

```
function [flux] = xflux(alpha,beta,theta,A,B) %first 2 are the number of
%length divisions, theta is the angle between the direction
% of the dipole and the vector perpendicular to the coil, and the last two
% are the lengths of the sides of the coil.
a=A/alpha; %the infintiesimal lengths of side A(dl)
b=B/beta; %the infintiesimal lengths of side B (dl)
d=[10,A/2-0.001,0,B/2-0.001]; %information on the dipole
mu_0=4*pi*10^(-7); %permeability of free space
m=pi/2-theta; %angle between the dipole and the plane of the coil
mhat=[-cos(m),sin(m),0];% dipole unit vector
flux=0; %set the flux to 0
flux1=0;
flux2=0;
flux3=0;
flux4=0;
for l1=A/2:-a:-A/2 %integral limits
x1=l1-d(1,2); %distance to the coil in all 3 dimensions
y1=-d(1,3);
z1=B/2-d(1,4);
r1=sqrt(x1^2+y1^2+z1^2); %radius to the section of wire acted on
r1hat=[x1,y1,z1]; %radius unit vector
A1=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r1hat)/r1^3); %Magnetic vector
%potential at that point on the wire
dl1=[-a,0,0];
flux1=flux1+dot(A1,dl1);%A*dl
```

```
end
for l2=B/2:-b:-B/2%repeat for side 2
x2=-A/2-d(1,2);
y2=-d(1,3);
z2=l2-d(1,4);
r2=sqrt(x2^2+y2^2+z2^2);
r2hat=[x2,y2,z2];
A2=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r2hat)/r2^3);
dl2=[0,0,-b];
flux2=flux2+dot(A2,dl2);
end
for l3=-A/2:a:A/%repeat for side 3
x3=l3-d(1,2);
y3=-d(1,3);
z3=-B/2-d(1,4);
r3=sqrt(x3^2+y3^2+z3^2);
r3hat=[x3,y3,z3];
A3=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r3hat)/r3^3);
dl3=[a,0,0];
flux3=flux3+dot(A3,dl3);
end
for l4=-B/2:b:B/2%repeat for side 4
x4=A/2-d(1,2);
y4=-d(1,3);
z4=l4-d(1,4);
r4=sqrt(x4^2+y4^2+z4^2);
r4hat=[x4,y4,z4];
A4=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r4hat)/r4^3);
dl4=[0,0,b];
flux4=flux4+dot(A4,dl4);
end
flux=flux1+flux2+flux3+flux4;%total flux through the wire
end
```

Code for finding the flux of a dipole precessing about the y-axis

```
function [flux] = yflux(alpha,beta,theta,A,B)%first 2 are the number of
%length divisions, theta is the angle between the direction
% of the dipole and the vector perpendicular to the coil, and the last two
% are the lengths of the sides of the coil.
a=A/alpha;%the infintiesimal lengths of side A(dl)
b=B/beta;%the infintiesimal lengths of side B(dl)
d=[10,A/2-0.001,0,B/2-0.001];%information on the dipole
mu_0=4*pi*10^(-7); %permeability of free space
m=pi/2-theta; %angle between the dipole and the plane of the coil
mhat=[0,sin(m),cos(m)];% dipole unit vector
flux=0;%set the flux to 0
flux1=0;
flux2=0;
flux3=0;
flux4=0;
for l1=A/2:-a:-A/2 %integral limits
x1=l1-d(1,2);%distance to the coil in all 3 dimensions
y1=-d(1,3);
z1=B/2-d(1,4);
r1=sqrt(x1^2+y1^2+z1^2);%radius to the section of wire acted on
r1hat=[x1,y1,z1];%radius unit vector
A1=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r1hat)/r1^3); %Magnetic vector
%potential at that point on the wire
dl1=[-a,0,0];
flux1=flux1+dot(A1,dl1);%A*dl
end
for l2=B/2:-b:-B/2%repeat for side 2
x2=-A/2-d(1,2);
y2=-d(1,3);
z2=l2-d(1,4);
r2=sqrt(x2^2+y2^2+z2^2);
```

```
r2hat=[x2,y2,z2];
A2=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r2hat)/r2^3);
dl2=[0,0,-b];
flux2=flux2+dot(A2,dl2);
end
for l3=-A/2:a:A/2%repeat for side 3
x3=l3-d(1,2);
y3=-d(1,3);
z3=-B/2-d(1,4);
r3=sqrt(x3^2+y3^2+z3^2);
r3hat=[x3,y3,z3];
A3=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r3hat)/r3^3);
dl3=[a,0,0];
flux3=flux3+dot(A3,dl3);
end
for l4=-B/2:b:B/2 %repeat for side 4
x4=A/2-d(1,2);
y4=-d(1,3);
z4=l4-d(1,4);
r4=sqrt(x4^2+y4^2+z4^2);
r4hat=[x4,y4,z4];
A4=(mu_0*d(1,1)/(4*pi))*(cross(mhat,r4hat)/r4^3);
dl4=[0,0,b];
flux4=flux4+dot(A4,dl4);
end
flux=flux1+flux2+flux3+flux4;%total flux through the wire
end
```

Code used to compare the values of the flux at several values of θ

```
F=zeros(3,10); %creates a 3x10 matrix of zeros
for t=0:1:9
theta=t*pi/18; %run flux test from theta=0 to theta=pi/2
f=yflux(1000,1000,theta,0.1,0.15);%phi=pi/2, precessing about the x-axis
```

```
g=xflux(1000,1000,theta,0.1,0.15);%phi=0, precessing about the y-axis
F(1,t+1)=theta;%first row is the theta value
F(2,t+1)=f;%second row is the flux values when phi=pi/2
F(3,t+1)=g;%third row is the flux values when phi=0
end
x=F(1,:); %x-axis is the angle
y1=F(2,:);%y-axis is the total flux
y2=F(3,:);
plot(x,y1,'x',x,y2,'o')%plots them side by side to compare them
xlabel('angle (radians)')
ylabel('Total Flux (T*m^2)')
legend('phi=pi/2','phi=0')
```

Mbed Code

```
#include "mbed.h"

DigitalIn DIn(p8);
DigitalOut DOut(p5);
AnalogIn In(A0);
AnalogOut Out(A3);
Serial pc(USBTX, USBRX); // tx, rx

float  P=0.067;
float  I=2.0;
int Npts=20;
float data[5000];
float sig_sum;
float Vin, Vout;
float Vint;
int ii;
float Verr;
```

```
int main() {
   while(1){


               // INTEGRATION

               // Shift data down one bin, add new measurement and average

        sig_sum=0.0;

        for (ii=0; ii<(Npts-1);ii++){
            data[ii]=data[ii+1];
            sig_sum=sig_sum+data[ii];
            }


             Vin=In.read()-0.5;  //SIG_IN
                if(Vin>0.5)Vin=0.5;
                if(Vin<-0.5)Vin=-0.5;

             data[Npts-1] = Vin;

                Vint=(sig_sum+Vin)/Npts;

    // Calculate Vout

                Vout= -(P*Vin +I*Vint);

              if (DIn==1) Vout=0.001;   //RESET

    if(Vout>0.5)Vout=0.5;
    if(Vout<-0.5)Vout=-0.5;
```

```
            Out.write(Vout+0.5);  //SIG_OUT
            DOut= !DOut;

  //      pc.printf("%6.4f \t %6.4f \t %6.4f \n",6.0*Vin,6.0*Vint,Vout*3.0);


 //      wait(0.02);
    }


}
```