University of Waterloo

Faculty of Science

Sweeping Magnetic Field Gradient on Neutral Atom Trap

TRIUMF - TRINAT

Vancouver, B.C.

Anya Forestell

20612722, 2B

27 April 2018

41 Lexington Lane
Fredericton, NB
Canada
E3A 5S6

27 April 2018

Dr. Brian McNamara, Department Chair
Department of Physics and Astronomy
University of Waterloo
Waterloo, Ontario
N2L 3G1

Dear Dr. McNamara:

This report, entitled "Sweeping Magnetic Field Gradient on Neutral Atom Trap," was prepared as my second of two 2B Work Reports; this term, I was employed at TRIUMF, working with the TRINAT group. This is my third work term report. The purpose of this report is to analyse whether sweeping magnetic field gradients improves TRINAT's results.

TRIUMF is a national research lab. It focuses on nuclear and particle physics, but also delves into molecular and materials science as well as nuclear medicine. Some experiments and research groups include TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science), GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei), and DRAGON (Detector of Recoils And Gamma-rays Of Nuclear reactions).

I worked with the TRINAT group (TRIUMF'S Neutral Atom Trap), with Dr. John Behr as my supervisor. My job was to assist in tasks related to implementing a sweeping magnetic field gradient on the atom trap, gather data, and analyse data. I also assisted with day-to-day tasks around the lab.

This report was written entirely by me and has not received any previous academic credit at this or any other institution. I would like to thank Dr. John Behr for his continued support and assistance in revising this report. I received no other assistance.

Sincerely,

(Signature)

Anya Forestell

20612722

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Summary

TRINAT studies the **weak interaction** by observing **beta decays**; most recently, the decay of potassium 37 into argon 37, a beta particle, and a neutrino. This is done by trapping and optically pumping atoms with laser light so that they become highly polarized. This allows scientists to properly measure the momentum of the recoil nuclei (argon 37) and beta particle. Using conservation of momentum, the momentum of the neutrino can thus be calculated and new physics beyond the Standard Model may be discovered. The purpose of this report is to analyse whether a gradient magnetic field created by **near-Helmholtz** coils can optimize the polarization of the atoms.

The coils were powered by TENMA power supplies. Several applications such as Moserial and CuteCom were used to attempt to communicate with the power supplies remotely; none of these worked properly, so a new Python code was written which worked very well.

A model was built to ensure the coils were working as expected; although there were some uncertainties on the results, the **anti-Helmholtz** and **Helmholtz** results were satisfactory enough to move forward. Two cameras were installed: one, a Grasshopper, was used to take pictures for later analysis. The second one, a Firefly, was used for real-time monitoring and calibrations.

A uniform magnetic field was created and balanced currents were swept through each coil; this returned an optimized magnetic field of -0.44A, confirming previous results. A gradient magnetic field was created by unbalancing sweeping currents; there was a possible sign of an increasing polarization towards larger gradients, but further data is needed to confirm these results.

It is recommended that better camera sensitivity be achieved to reduce noise in the results. A more efficient Octave code should also be written to accelerate data analysis.

1.0 Introduction

In order to help readers understand the context of this report, a brief overview of TRINAT shall be given. TRINAT studies the **weak interaction** by observing **beta decays** of various elements; most recently, potassium 37 has been used. In a beta decay, potassium 37 decays into a recoil nucleus (argon 37), a beta particle, and a neutrino. For trapping and polarization tests which do not require the observation of a decay, potassium 41 is used; it has similar optical frequencies and splitting as potassium 37. The goal is to measure the neutrino's momentum to then hopefully discover new physics beyond the Standard Model. The process to do so is described below.

Atoms are first gathered in TRINAT's first trap. Next, a laser beam pushes the atoms from the (smaller) first trap into the second, main trap. To confine the atoms to a cube with dimensions of roughly 1 mm, a process called optical molasses is used. Pairs of laser light are shone along each axis; photons hitting and being absorbed by the atoms impart their momentum to the atoms. The light is tuned at a slightly lower frequency than an atomic resonance; due to the **Doppler effect**, atoms absorb more photons coming from the direction the atoms are travelling towards. Thus, the atoms are slowed down until forces from all directions come to an equilibrium, bringing the atoms to a stop. **Anti-Helmholtz** coils, which create a quadrupole magnetic field which changes sign at the center, produce a linear restoring force bringing the atoms to the center of the trap chamber. The magnetic fields create a **Zeeman shift** in the atoms, causing them to absorb more photons coming from the the polarized light beam bringing them to the center of the trap chamber. This type of trap is called a Magneto-Optical Trap (MOT).

Next, the MOT is turned off so that the atoms can be optically pumped with laser light; the atoms thus become highly polarized. Higher polarization means the direction of recoiling nuclei can be better predicted once the atoms decay. Detectors are therefore placed in these predicted spots to measure the momentum of recoiling nuclei and beta particles. Using conservation of momentum, the momentum of the neutrino can then be indirectly measured and new physics may be found.

The magnetic field in the trap must be precise; therefore, **near-Helmholtz** coils are placed around the trap chamber to counteract the background magnetic fields due to the Earth and the cyclotron. At the moment, a uniform magnetic field is created by balancing the currents in the **near-Helmholtz** coils, but it is possible that the background magnetic field is changing throughout the trap.

The purpose of this report is to analyse whether a higher degree of polarization can be achieved by creating a gradient magnetic field in the trap instead of simply a uniform magnetic field. This will be done by taking pictures at three separate times: during the brief time between when the MOT is turned off and optical pumping begins, in the middle of optical pumping, and at the end of optical pumping. The more polarized an atom is, the less fluorescent it becomes. Thus, by comparing the level of brightness between the last pictures and the first pictures, a measure of the effectiveness of increasing magnetic field gradients can be found.

2.0 Power Supplies

The **near-Helmholtz coils** mentioned in the previous section will need power supplies to control their voltage and currents. TRINAT is using TENMA 72-2710 power supplies. Manuals for these supplies can be found in the folder */home/trinat/Documents/Manuals_Plans/TENMA* on the trinat@trinatblack3 computer.

Once these power supplies are connected to the coils, a way to communicate with them is needed. Although it is possible to manually set the voltage and current on the power supplies themselves, it is highly ineffective to have to get up from the computer every time a setting needs to be changed. This becomes increasingly inefficient when settings need to be changed rapidly or regularly.

2.1 Platforms to Communicate with Power Supplies

Note that the following platforms are not completely understood, and therefore cannot be controlled with complete ease. Certain commands do not work with these platforms. For full use of commands, please refer to section 2.3.2 Codes: Python. If one of the following platforms must be used rather than a Python code, consider using CuteCom, as it offers the widest range of understood commands.

There are several platforms which can be used to communicate with and send commands to the TENMA power supplies from a computer. Three which were tested are Moserial, CuteCom, and GtkTerm. Below are the results of the tests, including lists of which commands worked and which commands did not work.

Note that Moserial, CuteCom, and GtkTerm were first tested on the trinat@trinatblack3 computer. The results dictated which platform to use directly on the Raspberry Pi 2; the Raspberry Pi 2 is the device being used to control the power supplies for the real **near-Helmholtz coils**.

2.1.1 Moserial

Users of Moserial must follow the procedure below in order to connect their computer to the power supplies:

1. Settings > Users and Groups > TRINAT > Manage Groups > dialout > Properties: Check that TRINAT is part of group.
2. Settings > Users and Groups > TRINAT > Advanced Settings > User Privileges: Check off "Use Modems."
3. Follow the TENMA 72-2710 manual and Benjamin Sheldan's report instructions to connect through "Port Setup."
4. If users receive the error "ERROR: Can't open device," restarting the computer should work.

Once users are connected to the power supplies through Moserial, they should be able to send the commands listed in the power supply manual. The format and results of these commands are explained in the *72-2710_instructions.pdf* document, placed in the TENMA folder mentioned above. Table 1 below lists which commands worked and which did not work with Moserial.

Command	**Worked/Did not work**	**Notes**
ISET	Worked	Precision must be 1-2 decimal points (ex. 1.0 or 1.00)
ISET?	Did not work	
VSET	Worked	Precision must be 0-1 decimal points (ex 1 or 1.0)
VSET?	Worked once	Worked only in CC mode
LOCK	Worked	
IOUT?, VOUT?, OUT, STATUS?, *IDN?, OCP	Did not work	
RCL, SAV	Did not test	

Table 1. Moserial Commands Function Check.

2.1.2 CuteCom

To connect to the power supplies through CuteCom, users must use the command “cutecom &” in the command terminal. They may also need to type in the name of the port the power supplies are connected to manually; simply selecting a port from the drop-down menu may not work.

Table 2 below lists which commands worked and which commands did not work with CuteCom.

Command	**Worked/Did not work**	**Notes**
ISET, VSET	Worked	Worked at any precision
ISET?, VSET?, IOUT?, VOUT?, STATUS?	Worked	STATUS returns P or Q depending on whether it's limited by current or voltage
OUT, OCP	Did not work	
RCL, SAV	Did not work	Make some changes, but unclear how they function
LOCK	Worked	

Table 2. CuteCom Commands Function Check.

2.1.3 GtkTerm

Connecting to the power supplies using GtkTerm was a struggle. Eventually, it was discovered that users must "Save" the file containing the command to be sent, then "Send" the file. At this point, CuteCom was the preferred platform, so no rigorous command checks were performed with GtkTerm.

2.2 Raspberry Pi

Once CuteCom was determined as the most functional platform, it was tested on the Raspberry Pi 2. To find the name of the port through which the power supplies are connected, use the command "ls -lrt /dev" in the command terminal. The ports are usually named /ttyACM0 and /ttyAMA0. Using CuteCom on the Raspberry Pi 2 gave the same command function checks as on the trinat@trinatblack3 computer; refer to Table 2.

2.3 Codes

The next step was to integrate power supply commands into written codes. This was done for two reasons: first, CuteCom did not work for all commands. A code was needed to make them all work. Second, although CuteCom allows users to stay seated at their computer instead of manually changing the settings on the power supplies, it still requires them to manually send commands from their computer. A code was needed to automate the sending of commands and sync the power supply settings with the rest of the workings of the atom trap.

2.3.1 C++

Benjamin Sheldan wrote codes in C++ to control the power supplies; those studied were */RunTrapSequence_cp/power_sweep_cpp_test*.cpp*, on the pi@trinatrpi2 (Raspberry Pi 2). The initial code ended with *_jb.cpp*, while the code used for testing by the author of this report ended with *_af.cpp*. These codes are able to send ISET and VSET commands. Attempts to use these codes as templates to send other commands, particularly commands which asked for a response (ex. ISET?, VSET?, IOUT?, VOUT?), were made, but to no avail. Other commands were not understood by the power supplies.

Using this code, the set current was swept between 0A - 4.5A on the power supplies. There were some discrepancies between the set current, the displayed current, and the actual current measured by a BK Precision 316 Milliamp Clamp Meter on each power supply. The discrepancies between the set current and displayed current varied between 0.000A - 0.005A. The discrepancies between the set current and actual currents varied between 0.001A - 0.021A. The discrepancies between the displayed current and actual current varied between 0.000A - 0.018A. For a full table of the recorded data, please see page 3 in logbook *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)*.

2.3.2 Python

All Python codes written by the author of this report use Python version 2.7.12. To open a Python shell, use the command "python -m idlelib.idle" in the command terminal. From there, click File > Open to open the appropriate code. In January 2018, a new code was written in Python instead of C++. An older version, *python_communicate_powersupplies.py*, is stored on trinat@trinatblack3 under */home/trinat/Documents/Python_Codes*. The latest version, */python_trinat/power_supply_current_sweep.py*, is stored on pi@trinatrpi2. This Python code was very successful; all commands work using this code. Note that this Python code uses two separate pieces of code to send a command and to then read an answer from the power supplies. More details can be found in the # comments of the code itself.

The end-goal of this Python code was to be able to read in a number from another file, which then dictated the code's next steps. This allowed the Python code to be integrated with the rest of the workings of the trap, and to control the power supplies in sync with other components. For example, the camera, covered in section 4.0 of this report, needed to take pictures at the correct moment. All of these components worked in sync.

3.0 Near-Helmholtz Simulation

Before using the real **near-Helmholtz coils** around the trap chamber, a simulation was built in order to test the power supplies and the magnetic fields resulting from a current sweep. This simulation was based on the real set-up, but had slightly different dimensions.

3.1 Design

3.1.1 Real Trap Coils Design

Below, Figures 1. a) and b) are pictures of the real trap coils. Following the pictures, in Table 3, are the dimensions of the real set-up.

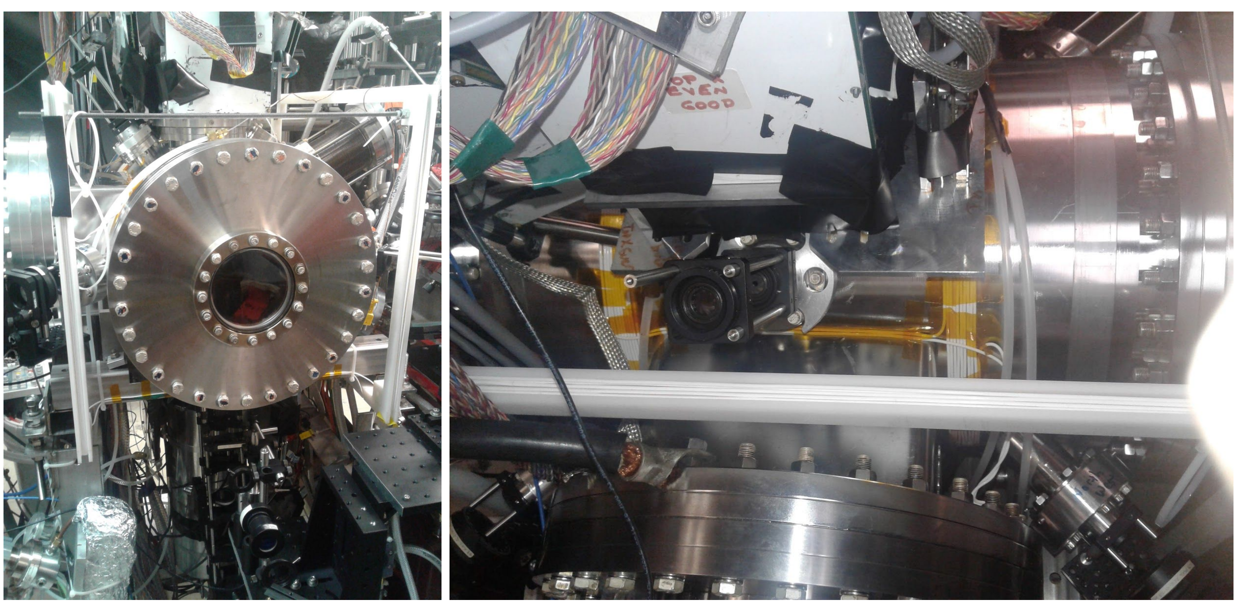

Figure 1. a) Outside of trap chamber. b) Overhead view of trap chamber, white near-Helmholtz coils are covered in yellow tape.

Description	Dimension (cm)
Width of one coil	2.2
Width of one loop of wire	0.22
Distance between centers of coils	24.3
Diameter of coils	31.75

Table 3. Dimensions of Real Trap Coils.

3.1.2 Simulation Design

Below, Figures 2. a) and b) show the simulation set-up. Following the pictures, Table 4 lists the dimensions of the set-up.

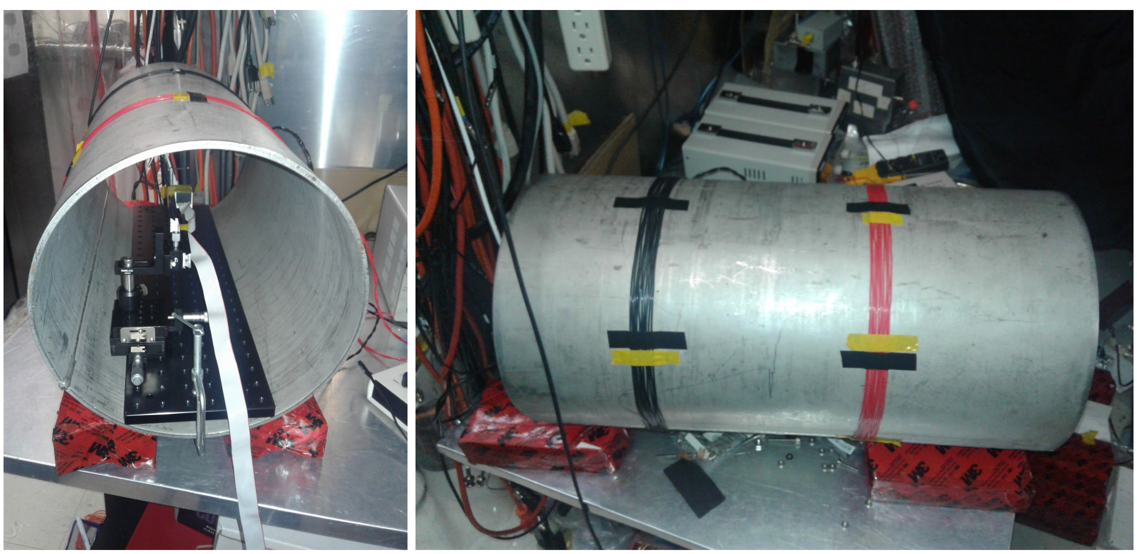

Figure 2. a) Outside view of simulation. b) Side view of simulation with black and red near-Helmholtz coils.

Description	**Dimension (cm)**
Width of one coil	2.3
Width of one loop of wire	0.23
Distance between centers of coils	24.2
Diameter inside steel cylinder	29.5
Diameter outside steel cylinder	30.5

Table 4. Dimensions of Simulation Trap Coils.

A first attempt to build a stage for the magnetic probe was attempted using only MT1 stages from Thorlabs. Due to the dimensions of this set-up, it soon became clear that it would not satisfy the location requirements for the probe. The probe was to be located in the center of the coils, with freedom to move 1 cm along each axis. For detailed information on the dimensions of this first set-up, please refer to page 5 of logbook *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)*. Further information on the stages' displacement limits can be found on page 6 of the same logbook.

A second stage design was therefore built, using two MT1 stages to move the probe along the x- and y- axes, while a DT12 stage was used to move the probe along the z-axis. The x-axis is horizontal, the y-axis goes into the cylinder, and the z-axis is vertical. Figure 3 below describes what is meant by x-, y-, and z-axes. Drawing projections of the MT1 stage can be found on the trinat@trinatblack3 computer under

/home/trinat/Documents/Manuals_Plans/MT1-AutoCADPDF.pdf, while more information on the DT12 stage can be found under */home/trinat/Documents/Manuals_Plans/DT12*. Table 5 below lists the expected and in-practice displacements of the stages.

Figure 3. Inside view of simulation; x-axis is horizontal, z-axis is vertical, and y-axis is going into cylinder.

Stage	**Expected (mm/turn)**	**In-practice (mm/turn)**
Lower MT1 (y-axis)	0.64	0.59557
Upper MT1 (x-axis)	0.64	0.59015
DT12 (z-axis)	0.35	0.35

Table 5. Expected and In-practice Displacement/Turn of Stages.

For more detailed information on the second stage set-up, please refer to pages 7-8 and 11 of the logbook *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)*.

3.2 Field measurements

Once the stage was properly set-up so that the magnetic field probe was located in the center of the coils, the simulation could proceed to measuring the field due to various currents in the coils. Tests were done for both **anti-Helmholtz** and **Helmholtz configurations**.

3.2.1 Anti-Helmholtz Configuration

As an initial test, the coils were set in **near-anti-Helmholtz configuration** and data was gathered on the fields along each axis for a current of approximately 4A. Note that although the command sent to the power supplies was 4A, the actual output was 3.998A.

First, the power supplies were turned on and the magnetic probe was moved around along the x-, y-, and z-axes until it found the point with the lowest magnetic field. From this point on, these coordinates were noted as the true center of the coils.

Next, the power supplies were turned off, and a measurement of the background field at the center was taken. It should be noted that the background field should be equal to the field at the center of the coils, as the magnetic fields from both coils should cancel each other out at the center. The background field was approximated as unchanging throughout the 1cm cubed area that the probe was to measure.

Finally, the probe was displaced in increments along each of the axes and a measurement of the magnetic field in all three directions was taken at each point. The full table of gathered data can be found on pages 9-10 of the logbook *TRINAT - Anya Forestell - Winter 2018 (Jan - April 2018)*. This data was also saved in the *fielddata*.txt* files under the */home/trinat/Documents/Python_Codes/helmholtz_simulation* directory of the trinat@trinatblack3 computer.

Python codes were then written to predict the expected magnetic field at each point. These codes can be found in the files *Magnetic_field_coils.py* and *B_field_xy_plane.py* in the */home/trinat/Documents/Python_Codes/helmholtz_simulation* directory of the trinat@trinatblack3 computer. The following equation was used to find the expected values of the magnetic field along the y-axis due to current in a loop:

$$B_y = \frac{\mu I}{2} \times \frac{R^2}{(y^2 + R^2)^{3/2}} \qquad (1)$$

Where By is the magnetic field in the y-direction, mu is the **permeability constant**, I is the current in the loop, R is the radius of the loop, and y is the distance from the loop along the y-axis. Equation (1) was taken from Benjamin Sheldan's April 2017 Work Report, where he derived this equation using **Ampere's Law** and **Biot-Savart's Law**. The Python codes take into account that there are 10 loops of wire in each coil, as well as two coils. Note that the Bx and Bz fields are zero along y-axis as they cancel out within each loop.

The following equations were used to the find the magnetic field along the x- and z-axis, in spherical coordinates:

$$B_r = \frac{I\pi R^2}{c} \cos\theta \frac{2R^2+2r^2+Rr\sin\theta}{(R^2+r^2 2Rr\sin\theta)^{5/2}} \qquad (2)$$

$$B_\theta = \frac{-I\pi R^2}{c} \sin\theta \frac{2R^2-r^2+Rr\sin\theta}{(R^2+r^2+2Rr\sin\theta)^{5/2}} \qquad (3)$$

Where Br and Btheta are the magnetic fields in the r and theta directions, r is the distance between the center of the loop and the point, theta is the angle between the y-axis and r, I is the current in the wire, R is the diameter of the loop, and c is the speed of light. Equations (2) and (3) were taken from page 178 of *Classical Electrodynamics: Second Edition* by J. D. Jackson (1962/1975).

Using these predictions, a new Python code was written to compare the expected magnetic fields to the gathered data. This code, *Plots_data_collected.py*, can be found in the */home/trinat/Documents/Python_Codes/helmholtz_simulation* directory on the trinat@trinatblack3 computer. Below, in Figure 4, plots of the results can be seen:

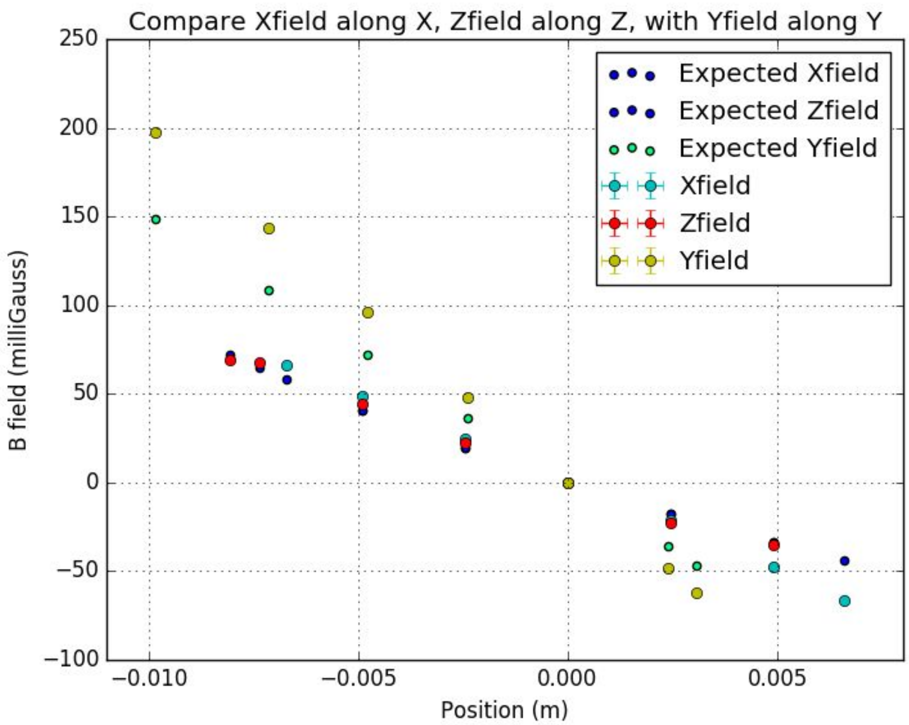

Figure 4. Comparison of Calculated B Fields using Equations (1) - (3) vs Measured B Fields.

3.2.2 Helmholtz Configuration

Next, the coils were set in **near-Helmholtz configuration**. This time, the current was not constant at 5A; rather, it swept through 1A - 5A. The full table of gathered data can be found on pages 11-13 of the logbook *TRINAT - Anya Forestell - Winter 2018 (Jan - April 2018)*. This data was also saved in the **Ahelmholtz.txt* files under the */home/trinat/Documents/Python_Codes/helmholtz_simulation* directory of the trinat@trinatblack3 computer.

A new Python code was written to predict the magnetic fields due to coils in a **near-Helmholtz configuration**. These were compared to the gathered data using the *updated_helmholtz_magfield_plots.py* file in the */home/trinat/Documents/Python_Codes/helmholtz_simulation* directory on the trinat@trinatblack3 computer.

Equation (3) was used once more to find the By field along the y-axis. However, a new equation was used to find the By field along the x- and z-axis:

$$B_y = \frac{\mu I}{\pi} \frac{(R^2 - r^2) \times E(k^2) + \alpha^2 \times K(k^2)}{2 \times \alpha^2 \times \beta} \qquad (4)$$

$$\alpha = (R^2 + r^2 - 2R\rho)^{1/2} \qquad (5)$$

$$\beta = (R^2 + r^2 + 2R\rho)^{1/2} \qquad (6)$$

Where constants represent the same values as in Equations 2-3, rho represents the radial distance from the axis (x or z coordinate) and E(k^2) and K(k^2) are **elliptical integrals** of the first and second kind. Equations (4), (5), and (6) were found on page 2 of *Simple Analytic Expressions for the Magnetic Field of a Circular Current Loop*, by Simpson et al. (n.d.). Note that the Bz expression in the paper is being used for this report's By expressions, as the axes are denoted differently in each case.

Equations for **elliptical integrals** can be found in the Python code mentioned above; these equations were approximated to the third term in K^2. Full equations can be found on pages 590-591 of the *Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables* by the U.S. Department of Commerce (National Bureau of Standards, Applied Mathematics Series - 55, 1964/1972), edited by M. Abramowitz and I. A. Stegun. The code shows relatively good correlations, with deviations on a very small scale. An example of a comparison is displayed below, in Figure 5. All comparison plots can be seen by running the *updated_helmholtz_magfield_plots.py* code mentioned above.

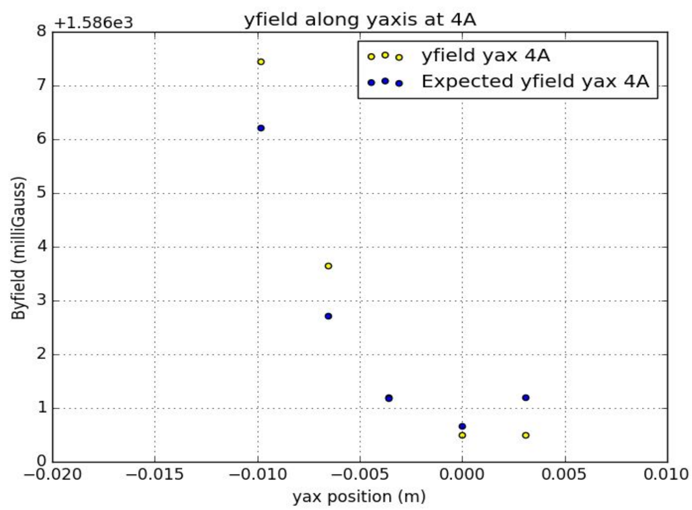

Figure 5. Comparison of Calculated B Fields using Equations (1) - (6) vs Measured B Fields.

4.0 Firefly Camera

Next, cameras needed to be properly set up and calibrated in order to capture images of the atom cloud as the power supplies swept through various currents. One such camera is the Point Grey Firefly MV camera. Its technical reference document, *Firefly-MV-Technical-Reference.pdf*, can be found in the */home/trinat/Documents/Manuals_Plans* directory of the trinat@trinatblack3 computer.

4.1 Set-up

In order to focus the light from the atom cloud and only that light, a series of light filters and lenses were used. Two red glass (RG695nm) filters were placed in series with a 250mm focus lens as well as a 30mm focus lens. The red glass filters reduce light from shorter wavelengths regardless of their angle. Drawings of the RG695 filters can be found in the */home/trinat/Documents/Manuals_Plans/RG695* directory on the trinat@trinatblack3 computer. More information on the optical glass properties, such as transmission, can be found in the *schott-optical-filter-glass-properties-2014-eng.pdf* document in the */home/trinat/Documents/Manuals_Plans* directory on the same computer. For more information on the lenses, refer to the */LAC181-B* and */AC254030B* directories within the */home/trinat/Documents/Manuals_Plans* directory on the same computer. Figure 6 below shows the set-up of each component.

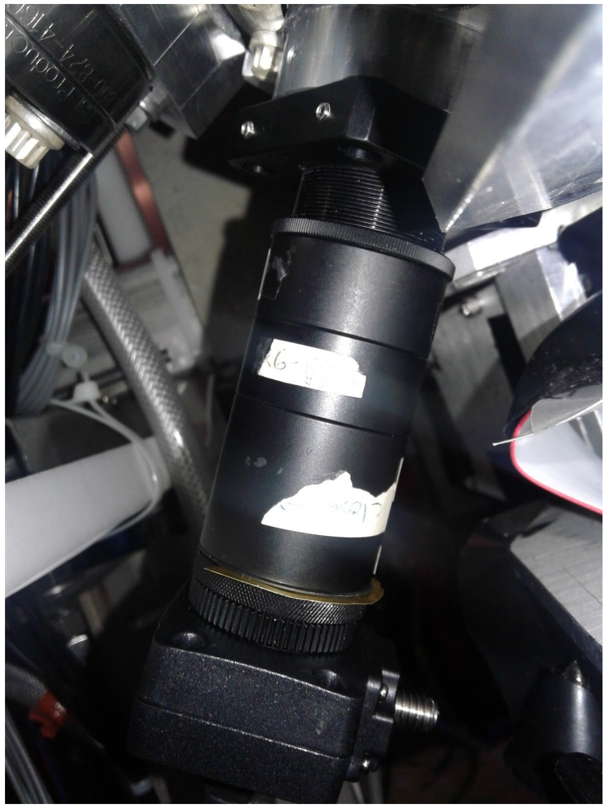

Figure 6. Firefly camera setup: camera at bottom, followed by 30mm lens, red glass filter, 250mm lens, with trap at the top.

The Effect of Inserting a Flat Glass Plate into the Optical Path Downstream from a Lens by Douglas A. Kerr (2007) was also consulted to understand how the port glass and the red glass filter affected the placement of the lens' focus point. The paper concludes that a plate of glass with thickness t and index of refraction n will displace the focus point by equation (7):

$$s = t(1 - \frac{1}{n}) \qquad (7)$$

Equation (7) was used to adjust our predicted focus point for the system of lenses. More information can be found on pages 19-20 of the logbook *TRINAT - Anya Forestell - Winter 2018 (Jan - April 2018)*.

4.2 Calibration

To calibrate the center of the image, the magnification of the image, as well as the focus of the image, two sets of pictures were taken. One set of pictures was taken with the camera set-up on the atom trap, with a lamp shining from a port on the other side to indicate the center. A second set of images were taken with the camera taken off the atom trap, using a target to indicate the center. These images were compared to two previously taken images of a rubidium 92 trapped atom cloud.

The application used to analyse and compare the images is called Octave. Octave codes were previously written by Erin Broatch. Copies of these codes as well as instructions on how to use them can be found in the */home/trinat/trinat/octave* directory on the trinat@trinatblack3 computer. Note that *af.m codes are codes initially written by Erin Broatch and updated by the author of this report to fit more current needs. *af.m codes should be used rather than *.m codes when available.

4.2.1 Trap and Lamp Images

First, images of lamp light from an opposite port were taken and compared to rubidium 92 images. The images mostly used in analysis were *lamp1.png*, *lamp2.png*, *trap92b.png*, and *trap92a.png*. Further images, *lamp3.png* through to *lamp16.png*, were also taken with different settings. These can all be found in the */home/trinat/trinat/octave* directory on the trinat@trinatblack3 computer. Refer to page 15 of the logbook *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)* for full details on the settings for each picture. Assume that previous settings are kept until it is noted they are specifically changed.

It is important to note that when using the imread(uigetfile()); command in Octave, it will record a XxYx3 matrix. Functions such as *projfitaf.m* and *sidwpaf.m* cannot analyse a three dimensional matrix. As such, the following commands must be executed before trying to pass an image to a function:

1. image = imread(uigetfile()); (then select the .png file to be analysed)
2. image = image(:, :, 1); (this will keep a full two dimensional version of the matrix)

Note that the commands can be executed with or without a semicolon at the end; a semicolon will simply repress the printing out of the matrix. Semicolons help with the readability of Octave’s command window.

In the case that there are serious unwanted backgrounds in the image, it can be useful to crop an image before analysing it. Here is an example for how to crop an image:

image_crop = image(a:b, c:d)

Where a and b are the pixel limits for the rows to be analysed, while c and d are the pixel limits for the columns to be analysed. Note that the rows start at the top of the image.

Various sizes of cropped images were used to analyse the lamp and rubidium 92 images. Full details of the cropping limits can be found on pages 13, 16-17, 19, and 21 of the *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)* logbook.

Using these images, the centroids of the clouds of atom and lamp light could be found and compared. The Octave code *projfitaf.m* was used to do this. Table 6 below displays the horizontal and vertical coordinates of the center of the clouds and lamp light. The camera is capturing a 480x640 pixel picture overall. Note that trap92a is less precise, as there is a much bigger background and the cloud appears much fainter; thus, it was more difficult to measure. More information can be found on page 13 of the *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)* logbook.

	lamp1	lamp2	trap92a	trap92b
Horizontal (pixels)	289.947	290.04	292.8023	293.5603
Vertical (pixels)	242.862	242.824	238	249.3293

Table 6. Coordinates for Center of Atom Clouds and Lamp Light.

The table above shows that the cloud images were roughly (3x1) pixels away from the center of the trap chamber. Furthermore, the Full Width at Half Maximum (FWHM) as well as the standard deviation of the gaussian fit was found for both trap images.

4.2.2 Target Images

Another important piece of information to be found was the size of the clouds. To find this, the magnification of the system of lenses needed to be found. To find the magnification, a new set-up was prepared to take another set of pictures; this time, a target was used to measure the center and the magnification. All target images can be found in the directory */home/trinat/trinat/octave/target_*.png*.

It should be noted that initial images were taken while the lenses were not aligned for the proper focus. The 250mm lens was adjusted first and pictures taken after this adjustment end with *_newfocus.png*. Following this, the 30mm lens was also adjusted, and pictures taken after this adjustment end with *_newnew.png*. All distances noted in the image titles indicate the distance between the target and the edge of the tube in which the 250mm lens is situated. The distances indicated are in mm x10 (i.e. target_2427_newnew.png means that the distance between the target and the edge of the 250mm lens tube is 242.7mm). Pictures annotated with *_bestfocus_* indicate that the picture was taken at the best visual focus seen.

As with the lamp and trap images, it was useful to crop the images in order to analyse them. Two croppings which were found to be useful were (101:400, 151:450) and (201:300, 251:350).

With these pictures, the centroids and magnifications were found both before and after the focus was adjusted. Before the adjustment, the center of the target was found to be at an average of (242x297) (rows x columns) with the picture as a whole being (480x640). The magnification of the cloud was roughly 0.1182. After the adjustment, the center of the target was found to be at an average of (241x332). The magnification of the cloud was about 0.12. The physical size of the camera pixels were 0.006 mm. The calibration for the physical size of an object at the center of the trap to its size in camera pixels is approximately 0.05 +/- 0.0022 mm/pixel. For full tables of measurements at different distances, see pages 16-17, 21 of the *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)* logbook.

These measurements, along with the FWHM of the clouds mentioned in the previous section, resulted in estimating a cloud size of roughly 1.5mm x 1.9mm at FWHM for trap92a, and roughly 1.2mm x 1.4mm at FWHM for trap92b. Further information can be found on page 19 of the *TRINAT - Anya Forestell - Winter 2018 (Jan-April 2018)* logbook.

Using the magnification and pixel distance in the previous section, the distance between the cloud and the center of the trap chamber can also be found: (0.15mm x 0.05mm) (horizontal x vertical) away from the center of the trap chamber, with an estimated uncertainty of 0.03mm.

5.0 Current Sweep

5.1 Uniform Magnetic Field

With everything in place, the current could be swept and the results observed. First, the currents were balanced in both coils to give a uniform magnetic field; this was done to confirm past results for balanced current setting optimization found by Erin Broatch. Erin found that the current setting with the most optimized polarization results was -0.44A.

The current was swept between -1.0A and 0.0A. The plot below shows the height of curve (proportional to the brightness of the cloud) for the second and third images taken; a lower brightness in later images demonstrates a higher polarization. Plot 7 below confirms that -0.44A does indeed provide an optimized setting for a uniform magnetic field.

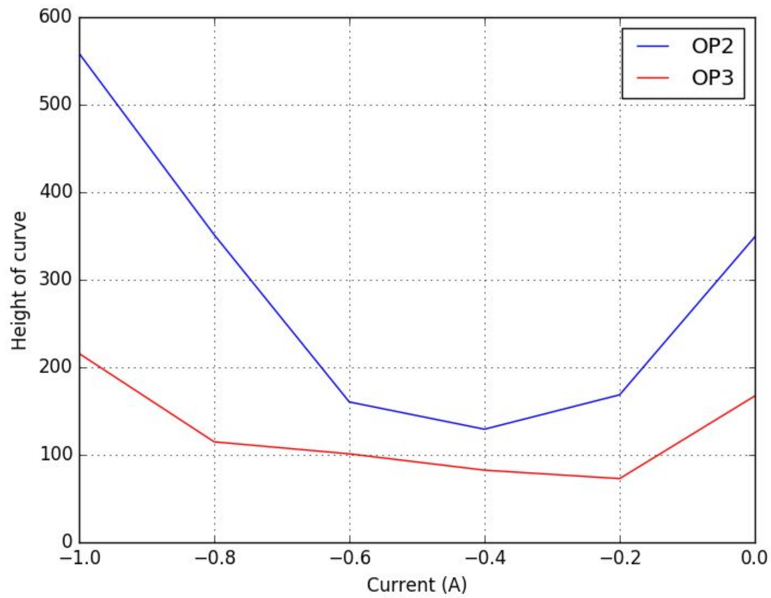

Figure 7. Height of brightness curve for second and third pictures (OP2 and OP3).

The *CustomImageEx2* code was used to run the camera and picture taking triggers. Refer to Erin Broatch's report for more information on this. Various Raspberry Pi and Python codes were used to run the trap and control the power supplies; please see the log files on the trinat@trinatblack computer, in the following directory: */home/trinat/Documents/CustomImageEx/log_apr*.txt*. The data for each picture taken is also kept in the */home/trinat/Documents/CustomImageEx* directory.

In Octave, *absc_af.m* was used to add all the correct images together. The *projfitaf.m* code was used to make projections on the accumulations of OP1 photos, also finding the standard deviation and mean; the standard deviation and mean must then be fixed in the *projfit_fixedaf.m* file to make projections on the accumulations of OP2 and OP3 photos. Both *projfit*af.m* codes also find the height of the curve and the area below the curve. These are then plotted against each current setting using various Python codes;

for balanced coils, */home/trinat/Documents/Python_Codes/tail_peak_ratios/plot_tail_peak.py* on trinat@trinatblack was used.

Note that normally, OP1 should be used to normalize OP2 and OP3; this was done in Section 5.2, Figure 9. However, in these datasets, OP1 demonstrated fluctuations hinting at an applied magnetic field not fully understood; thus, they were not used for normalization. A factor to keep in mind is that longer exposure time were used (300 microseconds), so it is plausible that fluorescence from longer optical pumping time was included in the OP1 exposures due to the imperfect magnetic field.

5.2 Gradient Magnetic Field

Once the optimized current for a uniform magnetic field was confirmed, the coils were unbalanced to create a gradient. The sweep was centered at -0.44A, with the coils sweeping outwards in steps of 0.08A. Preliminary sets swept out to -0.84A - -0.04A; later, the gradient was increased to sweep out to -1.32A - +0.44A.

The same Octave codes were used to analyse the pictures. Note that at this point, *projfitaf.m* was updated to write the results of its fit standard deviation and mean to a file for that set and also to write the height of its curve to a separate file. Then, *projfit_fixedaf.m* was updated to read in the standard deviation from the *projfitaf.m* file and use to to fix its FWHM, and also to write its resulting curve fit height to the same height file as *projfitaf.m*. Users of these codes must simply update the name of the files which these codes should write into. To plot the results,

/home/trinat/Documents/Python_Codes/tail_peak_ratios/plot_tail_peak_unbalanced.py*

on the trinat@trinatblack computer were used. These codes automatically pull the heights of the curves from the *projfit*af.m* files. The results are plotted below in Figure 8. a), b), c), and d). As can be seen in these plots, there are no clear trends.

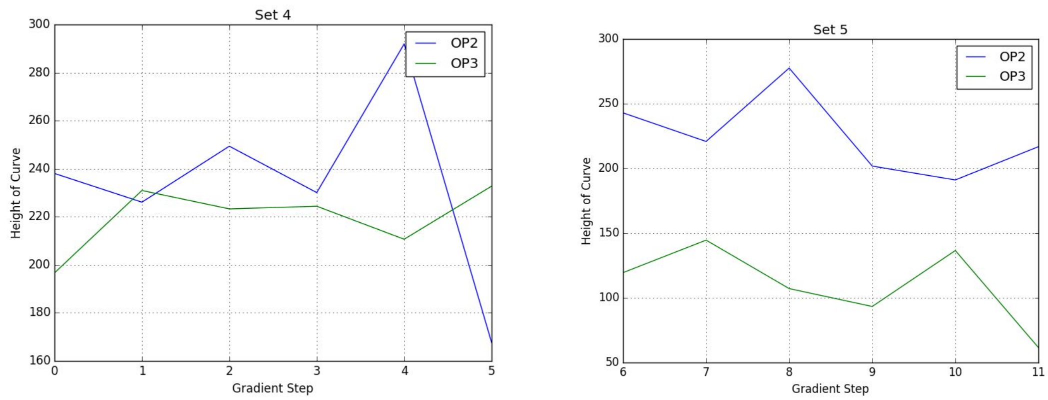

Figure 8. a) April 20th: Set 4, gradient steps 0-5. b) April 20th: Set 5, gradient steps 6-11.

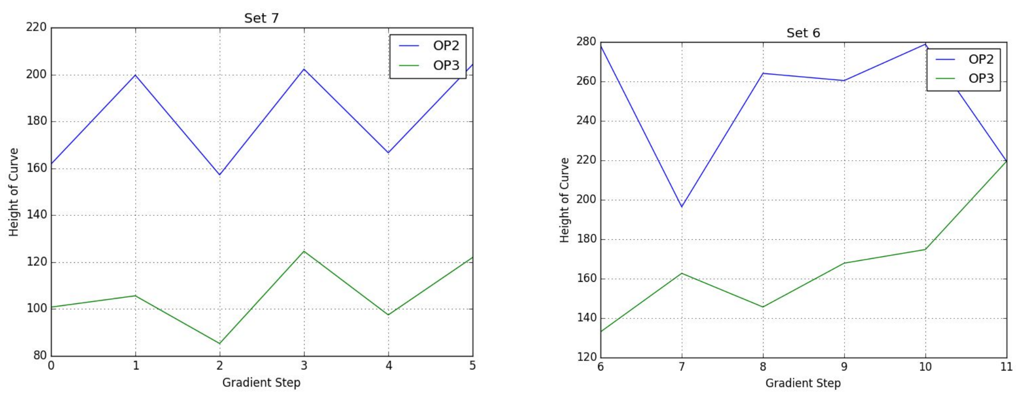

Figure 8. c) April 20th: Set 7, gradient steps 0-5. d) April 20th: Set 6, gradient steps 6-11.

At this point, the biggest gradient measured was only around 3.3 mG/mm; this is small given that the magnetic field at the center of the trap chamber (with a current of -0.44A) is around -175 mG. Thus, a bigger gradient was swept. The coils were kept centered at -0.44A, but were set to start at -0.88A and 0.00A to circumvent the need to change the sign on a power supply in the middle of a sweep. The currents were then swept out to -4.88A and +4.00A in steps of 0.8A. This was done in both directions by switching the signs and starting points on the power supplies between data sets. This gave a gradient of up to 16.3mG/mm. The results are shown below in Figure 9. a) and b); OP2/OP1 is in blue, OP3/OP1 is in red.

Note that up until sets taken on April 25th, pictures were taken in groups of 8. Starting with April 25th, set 4, pictures were taken in groups of 4 as for some unknown reason the camera code only took 5-7 pictures instead of the expected 8. However, the Raspberry Pi C++ code reported strobes from every trigger, meaning the camera should have received all the triggers. It is possible that 50 milliseconds is not long enough for each image to be properly written to the hard disk.

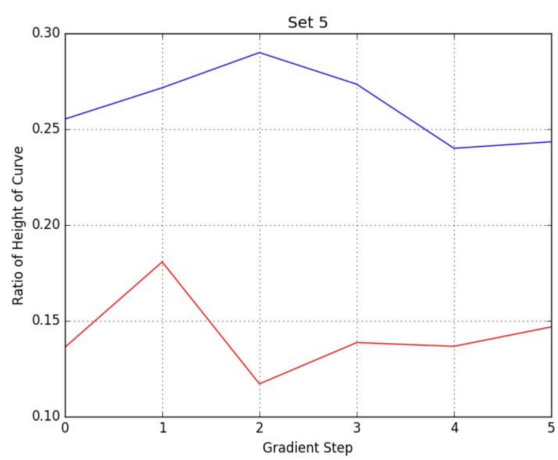

Figure 9. a) April 25th: Set 5.

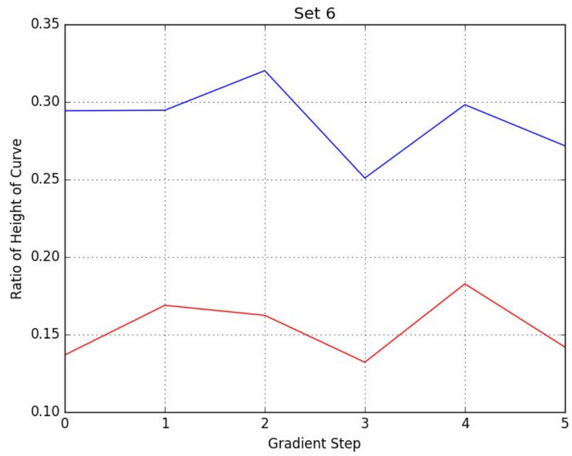

Figure 9. b) April 25th: Set 6.

Physica was then used to find errors on the projection fits and create a combination plot (Figure 10 below) of sets 4-6. A linear fit (in cyan) was also found for OP3/OP1 of set 4, with a slope of - 0.0011 +/- 0.0009 mm/mG. Set 6 is plotted as the negative values in red and black, set 5 is plotted as the positive values in red and black, and set 4 is plotted as the positive values in blue and green. Note that set 4 was given a slight offset in order to clearly see both sets 4 and 5.

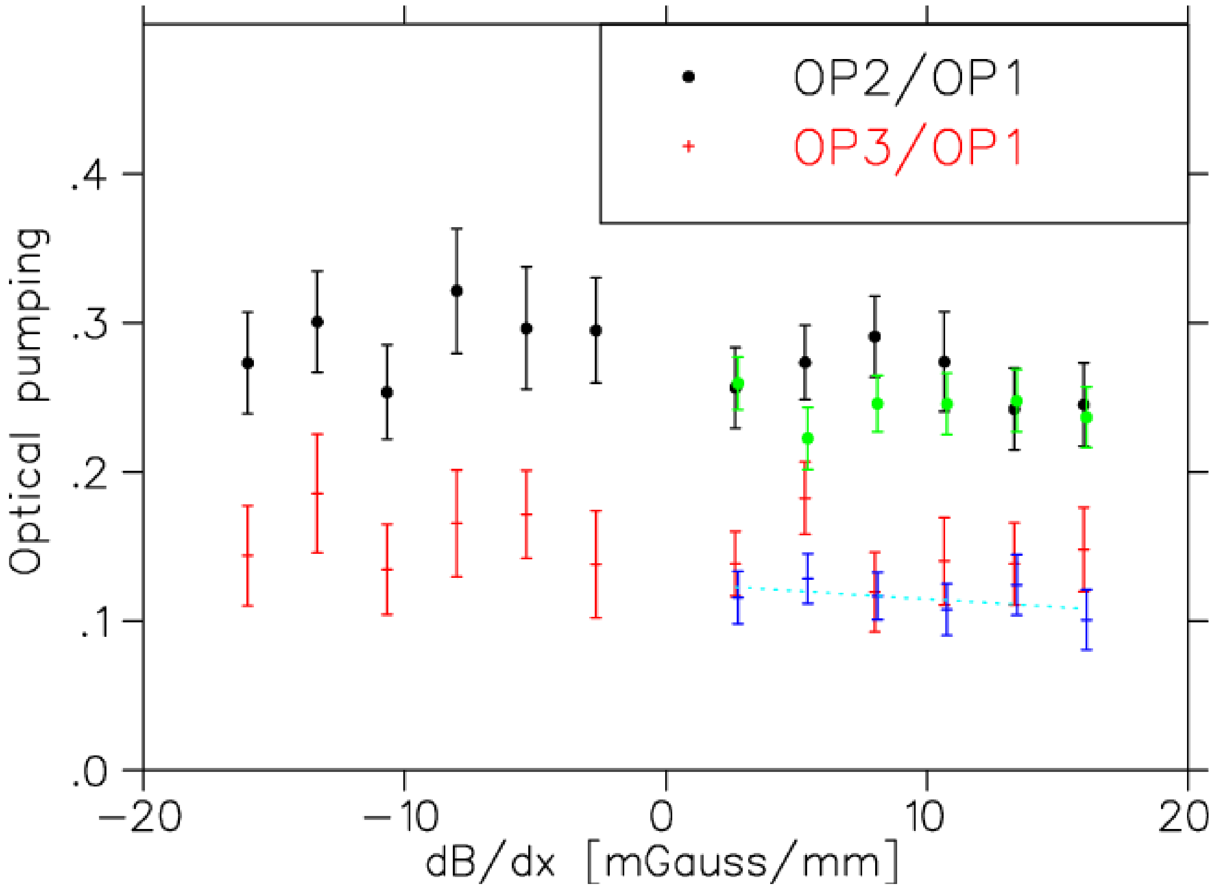

Figure 10. Optical Pumping Ratios for April 25th: Sets 4-6.

As denoted by the fit and observed for the other data sets as well, there seems to be a slight negative slope for all datasets. It would be worth pursuing a larger gradient in the positive direction and analysing whether this improves the optical pumping results.

6.0 Conclusions

Several positive conclusions can be made from this report:

- Avoid using applications to communicate with the TENMA power supplies, the Python code works very well and should be the preferred method of communication. If an application must be used CuteCom provided the widest range of functioning commands.
- The **near-Helmholtz** simulation demonstrated that both the **Anti-Helmholtz** and **Helmholtz coils** performed as expected.
- The center of the Firefly camera sensor is about 12 x -1 (horizontal x vertical) pixels off from the center of the frame of the camera itself; keep this in mind when making measurements. Furthermore, the cloud is approximately 0.15mm x 0.05mm off from the center of the trap chamber. The magnification of the Firefly camera and its system of lenses was about 0.12 at the center of the trap chamber, giving a calibration of approximately 0.050 +/- 0.0022 mm/pixel.
- A balanced current sweep creating a uniform magnetic field confirmed Erin Broatch's previous report of an optimized current at -0.44A.
- It is possible there is a slightly better polarization of the atoms at larger gradients, as demonstrated in Figure 10. Further data would be needed to confirm this.

7.0 Recommendations

1. Create a predictive model

   So far, data has been taken simply to see what would happen, without clear expectations of what should happen. Creating a predictive model and comparing the data to it may help clarify whether the data is credible or not.

2. Gather more data

   It is very often useful to continue gathering more data; with more data, clearer trends could start appearing. It may also be helpful to gather data in smaller gradient steps to see what happens between the data points already gathered.

3. Sweep bigger gradients

   So far, the biggest gradient measured was around 16.3 mG/mm; the magnetic field at the center of the trap chamber (with a current of -0.44A) is around 175 mG. It is possible that sweeping bigger gradients may reveal a clearer trend. The TENMA power supplies currently being used are only able to reach currents of 5.1A, so new power supplies capable of attaining higher current values would need to be installed.

4. Develop or obtain higher probe sensitivity

   The data gathered contains a lot of noise, which makes it difficult to make credible projection fits. Developing higher probe sensitivity could help eliminate some of the noise.

5. Create automated Octave codes for analysis

The process currently used to analyse the data sets is still a work in progress; creating automated Octave codes would help accelerate the process and make it more efficient.

8.0 References

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9.0 Glossary

Ampere's Law: A well-known physics law describing the relationship between a loop path, parallel magnetic field, permeability, and enclosed current, represented by the following equation:

$$\sum B_{||}\Delta l = \mu_0 I$$

Anti-helmholtz coils: Similar to Helmholtz coils, but with coil currents running in opposite directions, creating a quadrupole magnetic field.

Beta decay: A type of radioactive decay resulting in the emission of a beta particle (electron or positron).

Biot-Savart's Law: A well-known physics law describing the relationship between permeability, current running in a wire, the radius of a wire, and the magnetic field created by the current in the wire, represented by the following equation:

$$B = \frac{\mu_0 I}{2\pi r}$$

Doppler effect: A shift in wave frequency caused by a change in motion between a wave and an observer.

Elliptical integrals: Type of integral used in integral calculus, often used to express an ellipse's arc length.

Helmholtz: Set of two coils used to create a magnetic field; their radius (r) and distance apart (d) are equal (i.e. r = d). Note that *near*-Helmholtz coils do not perfectly have r = d.

Permeability constant: A well-known constant representing the resistance in the formation of a magnetic field in free space.

Weak interaction: One of the four fundamental interactions; it is governs radioactive decay.

Zeeman shift: The splitting of spectral lines when a static magnetic field is present.