

# Transporting Atoms Using a Magnetic Coil Transfer System

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## Abstract

Transporting atomic clouds using magnetic coils is a well-known and commonly implemented technique. Designs most commonly consist entirely of magnetic coils or involve the physical movement of coils. We would like to implement a magnetic coil transport system made entirely of magnetic coils in our new experiment. This paper details our preliminary development of the design for our magnetic coil transport system.

# 1 Introduction

In our experiment, we work with ultracold fermion gases. Using a magnetic field, we are able to tune the interaction strengths between these atoms. This is called Feshbach resonance and is the essential tool for controlling the interactions between atoms [1]. We work with strongly interacting  $^{40}\text{K}$  atoms. In this strongly interacting regime, the two body scattering length diverges and a perturbation approximation to the interactions between the atoms no longer holds (this approximation is valid when the atoms are weakly interacting).

We are currently working on constructing a new experiment. In our new ultracold Fermi gas experiment, we would like to use three ultrahigh vacuum chambers. The first chamber is used to collect  $^{40}\text{K}$  in a magneto-optical trap (MOT) which is then transferred to the second chamber using a push beam. This second chamber will hold the atoms in a MOT until they are transferred to the final chamber, where the experiment is run. To transfer to the final chamber, a magnetic coil transfer system will be used. A ninety degree bend is added in the transfer path to the final vacuum chamber. This allows for more optical access in the final chamber. Using the magnetic coil transfer system, it will be possible to transfer the gas cloud around this bend. The most significant feature of the final chamber is that it will not have a MOT, which will provide drastically improved optical access in the final chamber as opposed to the current two chamber setup where the experiment's chamber has a MOT.

$^{40}\text{K}$  has a magnetic moment of a Bohr magneton. Due to the Zeeman Effect, when  $^{40}\text{K}$  is placed in a magnetic field, the energies of the  $^{40}\text{K}$  atoms will split according to,

$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

where  $\vec{\mu}$  is the magnetic dipole moment. It is easily seen from this scalar product that depending on the magnetic dipole moment, the atoms will either shift to regions of high or low magnetic field. These states are called high and low-field-seeking states respectively. Maxwell's equations prevent a maximum in magnetic field strength in free space; therefore we will want to produce a minimum in magnetic field strength and work with low field seeking states.

It is simple to produce a minimum in a magnetic field strength using magnetic coils carrying current in opposite directions. Because the coils carry current in opposite directions, they create a quadrupole trap. The aspect ratio can be held constant during the transfer process with the proper choice of current in the coils as will be discussed more in Section Five below.

## 2 Background

The magnetic field in each coordinate direction of a current carrying coil of radius  $R$  perpendicular to the  $z$  axis centered at  $(x_0, y_0, z_0)$  are given by [2]

$$B_x = \frac{\mu_0 I}{2\pi\rho} \frac{z - z_0}{\sqrt{(R + \rho)^2 + (z - z_0)^2}} \frac{x - x_0}{\rho} \left( -K(k) + \frac{R^2 + \rho^2 + (z - z_0)^2}{(R - \rho)^2 + (z - z_0)^2} E(k) \right)$$

$$B_y = \frac{\mu_0 I}{2\pi\rho} \frac{z - z_0}{\sqrt{(R + \rho)^2 + (z - z_0)^2}} \frac{y - y_0}{\rho} \left( -K(k) + \frac{R^2 + \rho^2 + (z - z_0)^2}{(R - \rho)^2 + (z - z_0)^2} E(k) \right)$$

$$B_z = \frac{\mu_0 I}{2\pi} \frac{1}{\sqrt{(R + \rho)^2 + (z - z_0)^2}} \left( K(k) + \frac{R^2 - \rho^2 + (z - z_0)^2}{(R - \rho)^2 + (z - z_0)^2} E(k) \right)$$

where the argument of the complete elliptic integrals  $K$  and  $E$  is,

$$k = \frac{4R\rho}{(R + \rho)^2 + (z - z_0)^2}$$

and,

$$\rho = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$$

It should also be noted that  $I = NI_0$  where  $N$  is the number of turns in the coil and  $I_0$  is the current running through the coil. Using these equations, it is simple to find the magnetic field of a system of coils. It is also easily shown that two coils carrying current in opposite directions separated by some distance create a quadrupole trap, as seen in Fig. 1.

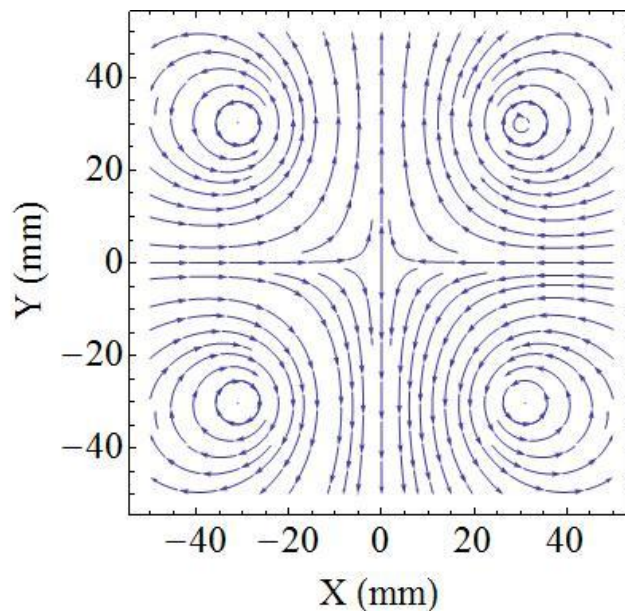


Figure 1: Magnetic field lines of a quadrupole trap produced by two coils of radius 30 mm with current running in opposite directions

We would like to make the approximation that the magnetic field of the coils is linear in the region of interest of the quadrupole trap. We would like to do this because it will drastically

simplify our calculation of the cloud size in Section Four. To check this approximation, the magnetic field of a coil in the x-direction was fit to a line.

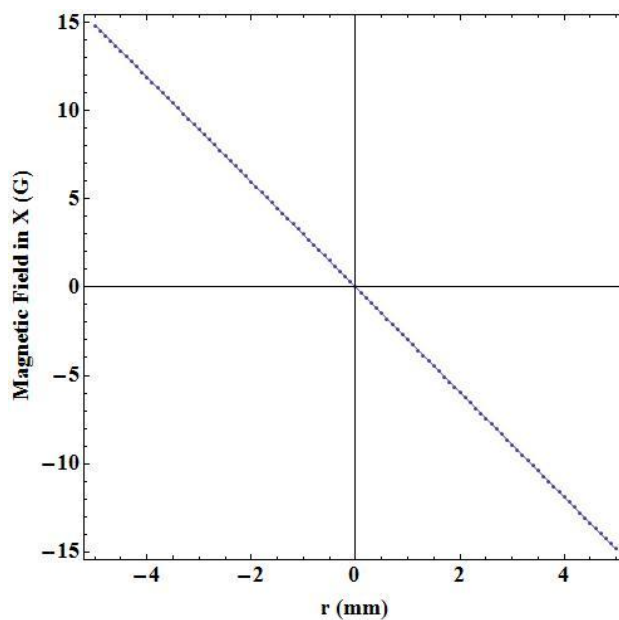


Figure 2: The magnetic field along the transfer direction for a given distance from the minimum in the field for a single pair of coils carrying 1200 A-turns. The data is fit to a line.

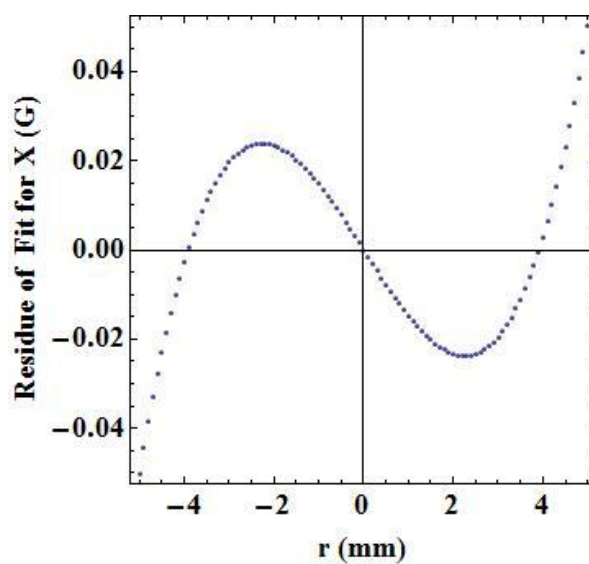


Figure 3: The residue of the fit in Fig. 2

It can be seen from Figures 2 and 3 that although the magnetic field is not actually linear, but for our purposes we can treat it to be linear. The deviations from the linear fit are on a much smaller scale than the strength of the magnetic field. This is also the case for the other two components of the magnetic field. This same analysis was done for a system of two pairs of coils carrying equal current. It can be seen in Figures 4 and 5 that the magnetic field can be taken to be approximately linear.

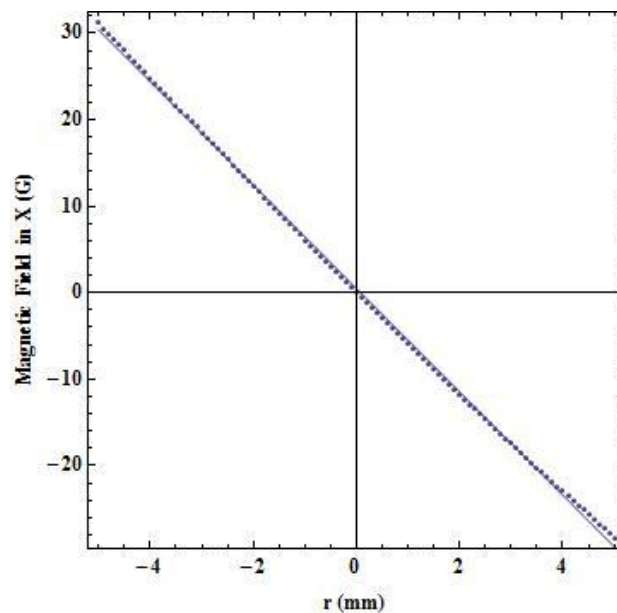


Figure 4: The magnetic field along the transfer direction for a given distance from the minimum in the field for two pair of coils carrying 1200 A-turns. The data is fit to a line.

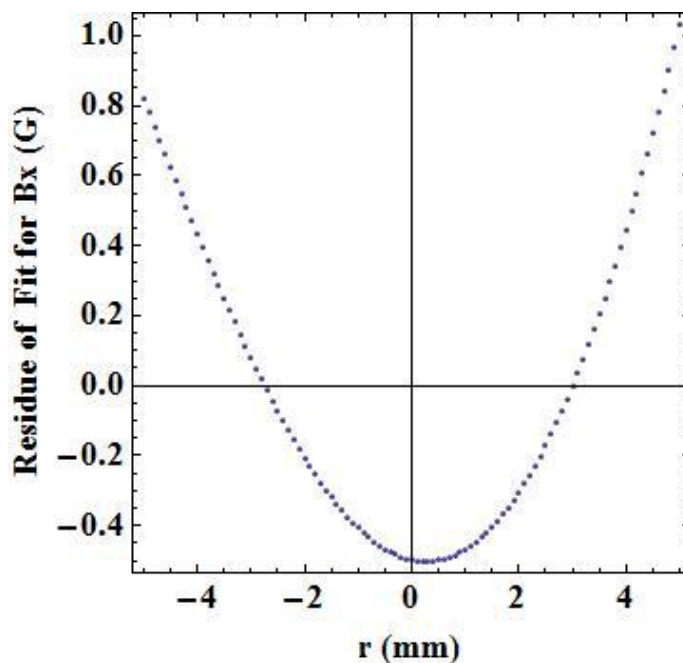


Figure 5: The residue of the fit in Fig. 4

It is also worth noting that the potential due to gravity corresponds to a gradient of 7.01 G/cm while the gradients to produce a cloud of radius 1.5 mm are 29.8 G/cm. Thus it may be necessary to correct for gravity. Using formulas for coils, it is possible to estimate the properties of a coil with a radius of 3 cm of 18 AWG wire. It should also be noted that the force exerted on one coil by another is about 2 N. In the final apparatus, the coils will need to be well secured to the mounting apparatus.

### 3 Required Trap Depth for Gas Clouds

The transported gas clouds will be at a temperature on the order of 100  $\mu\text{K}$ , which is many times larger than the Fermi energy, and thus they will behave classically. The velocities,  $v$ , of the atoms in a gas cloud will follow the 3D Maxwell-Boltzmann Distribution,

$$f(v) = \sqrt{\frac{2}{\pi}} \frac{v^2}{\tilde{v}^3} \exp\left(-\frac{v^2}{2\tilde{v}^2}\right)$$

where  $\tilde{v} \equiv \sqrt{k_B T / M}$  is the average velocity of the cloud,  $k_B$  is Boltzmann's constant,  $T$  is the temperature of the cloud, and  $M$  is the mass of an atom. The quadrupole trap must be deep enough to capture the desired fraction of the total atoms but must also be tight enough to fit inside of the transfer tube. These two conditions are determined by the geometry of the coil pairs and the current running through them. The fraction of atoms with a velocity less than or equal to some maximum velocity can easily be found by integrating the Maxwell-Boltzmann Distribution. This maximum velocity can easily be converted into energy. Then dividing by the thermal energy of the cloud, we obtain the plot in Fig. 6. This figure shows for a given trap depth,  $E$ , the fraction of the atoms that have a kinetic energy less than or equal to this trap depth, and hence are captured by the trap.



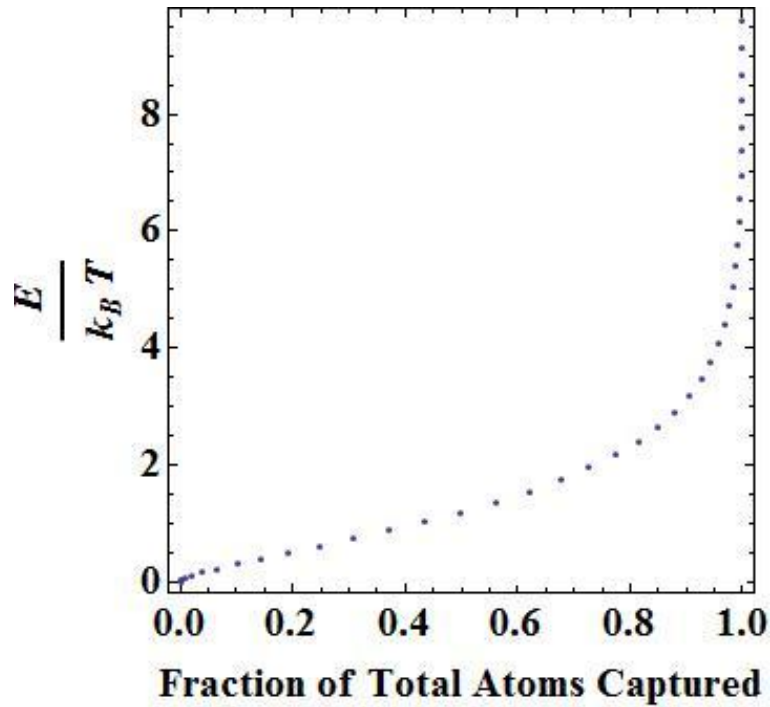


Figure 6:  $E/k_B T$  as a function of the fraction of the total atoms for a 3D Maxwell-Boltzmann distribution

## 4 Size of Gas Cloud in Trap

Because the approximation that the magnetic field is linear in the trap holds, the size of the cloud is entirely determined by the magnetic field gradient at the center of the trap. We would like to produce a quadrupole trap with a large enough field gradient such that a cloud of a certain temperature will be small enough to go through the transfer tube. The size of the cloud is given by

$$U = k_B T = \mu \alpha |x|$$

where  $\mu$  is a Bohr magneton, which is the magnetic dipole moment of  $^{40}\text{K}$ ,  $\alpha$  is the field gradient at the minimum of the magnetic field, and  $|x|$  is the radius of the cloud. Setting this equal to the

thermal energy of the cloud allows the size to be determined. The size of the cloud for a given gradient can be seen in Fig. 7.

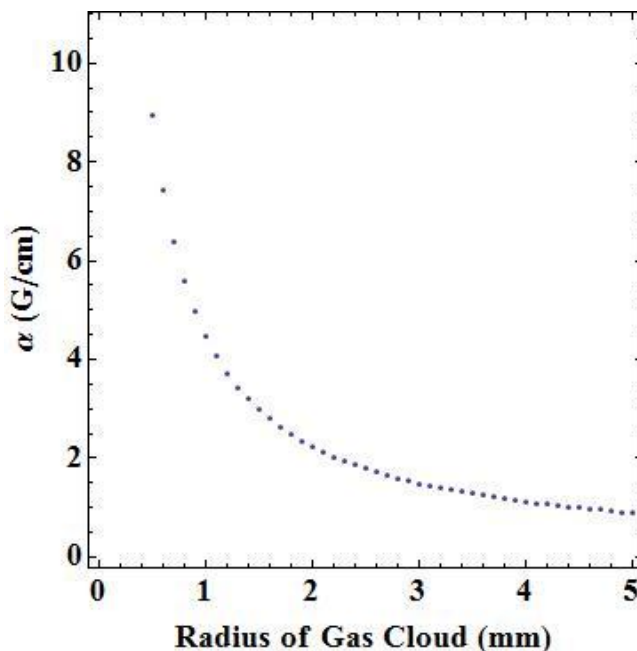


Figure 7: The magnetic field gradient at the minimum in the magnetic field of the trap necessary to produce a gas cloud of a certain radius.

## 5 Solving for Current in Coils

We would first like to generally solve for the current in the coils as a function of position along the transfer axis that maintain a constant aspect ratio of the trap. Note this is solving for the currents during the steady state of the transfer process. The aspect ratio of the trap must initially be changed because the cloud is initially spherical when held in the MOT. To do this, we will work with three coils at any given position; any less and you cannot maintain a constant aspect ratio [3]. Since we are working with the current in three coils, we constrain three parameters of

the trap: the sum of the magnetic field in the x-direction, the sum of the y-direction magnetic field gradients, and the sum of the z-direction magnetic field gradients.

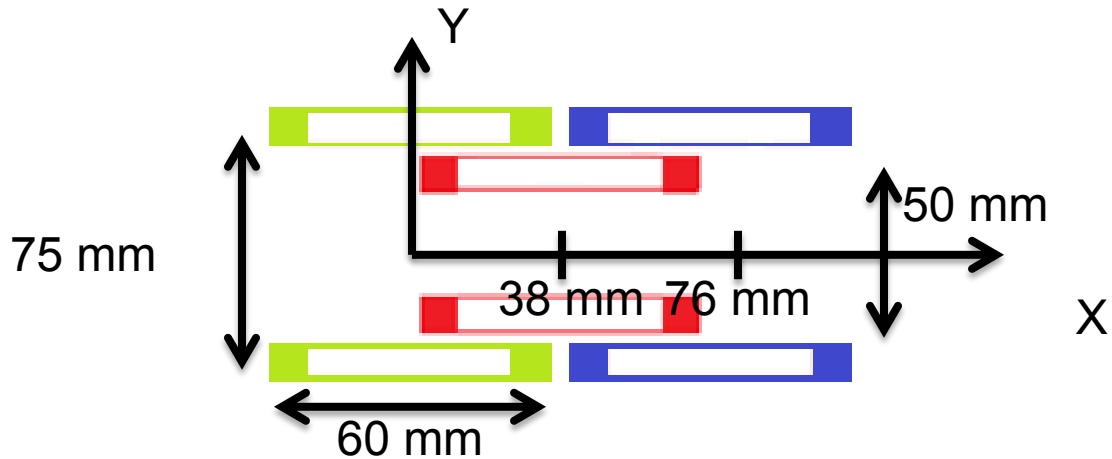


Figure 8: System of coils used to solve for the currents as a function of position

The result of the applied constraints is the following system of linear equations [4],

$$B_{1,x}(x)I_1(x) + B_{2,x}(x)I_2(x) + B_{3,x}(x)I_3(x) = 0$$

$$\beta_{1,y}(x)I_1(x) + \beta_{2,y}(x)I_2(x) + \beta_{3,y}(x)I_3(x) = \beta_y$$

$$\beta_{1,z}(x)I_1(x) + \beta_{2,z}(x)I_2(x) + \beta_{3,z}(x)I_3(x) = \beta_z$$

where  $I_1(x)$ ,  $I_2(x)$ , and  $I_3(x)$  are the currents in the coils as a function of  $x$ .  $B_{i,x}(x)$  denotes the magnetic field per amp in the x-direction for the  $i$ th coil.  $\beta_{i,j}(x)$  denotes the calculated magnetic field gradients per amp for the  $i$ th coil in the  $j$ th direction.  $\beta_y$  and  $\beta_z$  fix the strength at the center of the trapping potential made by the three coils. In solving this system, these gradients were picked to be 58 G/cm and 100 G/cm respectively. Fig. 9 shows the currents for each of the three coils found from solving this linear system. The region in which this system can be solved is

actually fairly limited. This is due to the fact that we are limiting ourselves to just three coils. To solve outside the current solvable region, we would have to consider a different set of three coils.

To solve for the currents of the entire transfer process, this process of solving in the solvable region for a set of three coils simply needs to be repeated for the entire transfer axis.

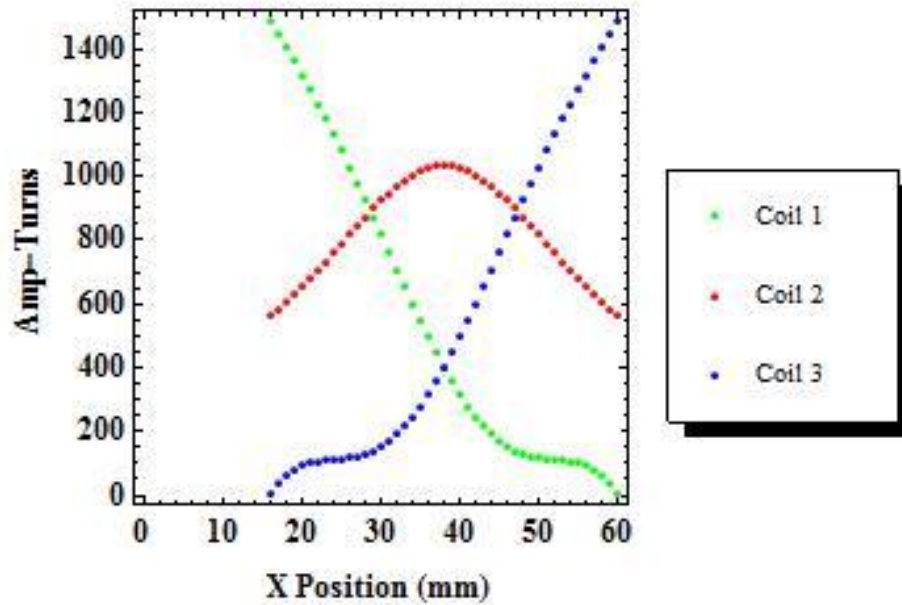


Figure 9: Current in each of the three coils required to maintain the conditions of the linear system as a function of position

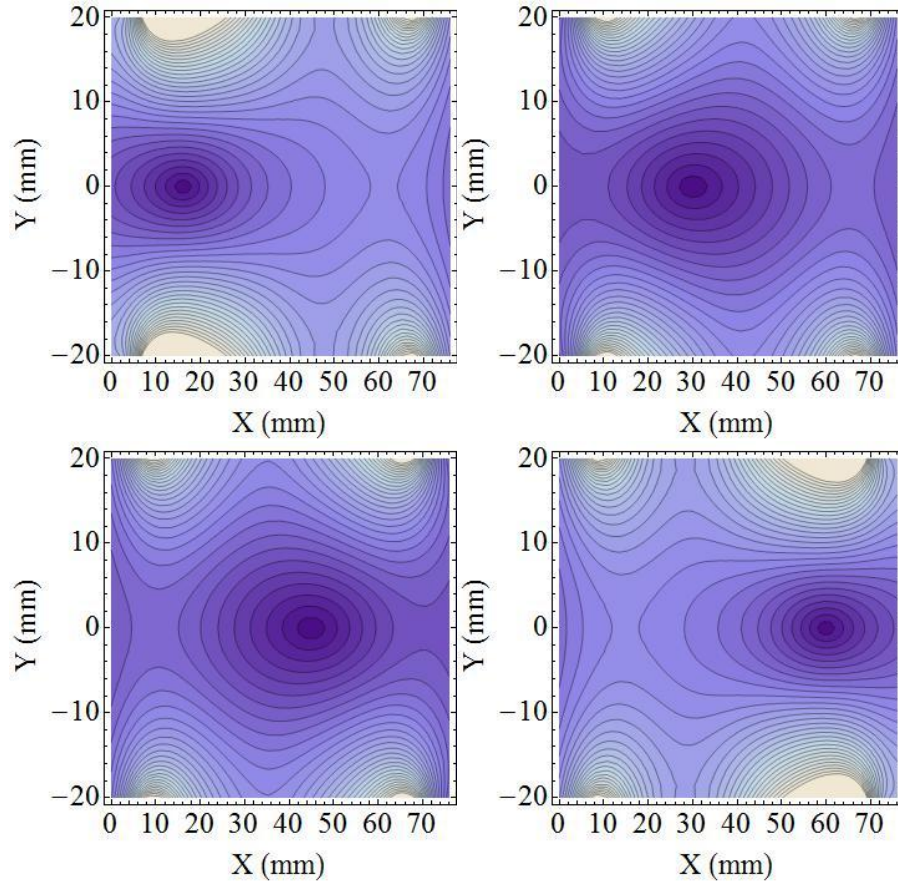


Figure 10: Contour maps of the magnitude of the magnetic field using the results of Fig. 9

Using the results from the analysis shown in Fig. 9, we were able to check whether the trap's aspect ratio remains constant throughout the transfer process. The contour maps in Fig. 10 of the magnitude of the magnetic field show that the aspect ratio of the trap does remain relatively constant.

## 6 Electronics

The entire transfer process will take on the order of one second and the currents required for transfer peak at around 30 A. Thus we will need to be able to drive these coils very quickly.

We also need to be able to drive these coils to the desired current very accurately. Any errors will lead to the aspect ratio of the trap changing and thus heating of the atoms. We will use a servo circuit, which servos off of the current in the coils via a hall probe, to drive a FET which will then control the current in the coils. A schematic of the circuit is shown in Fig. 11.

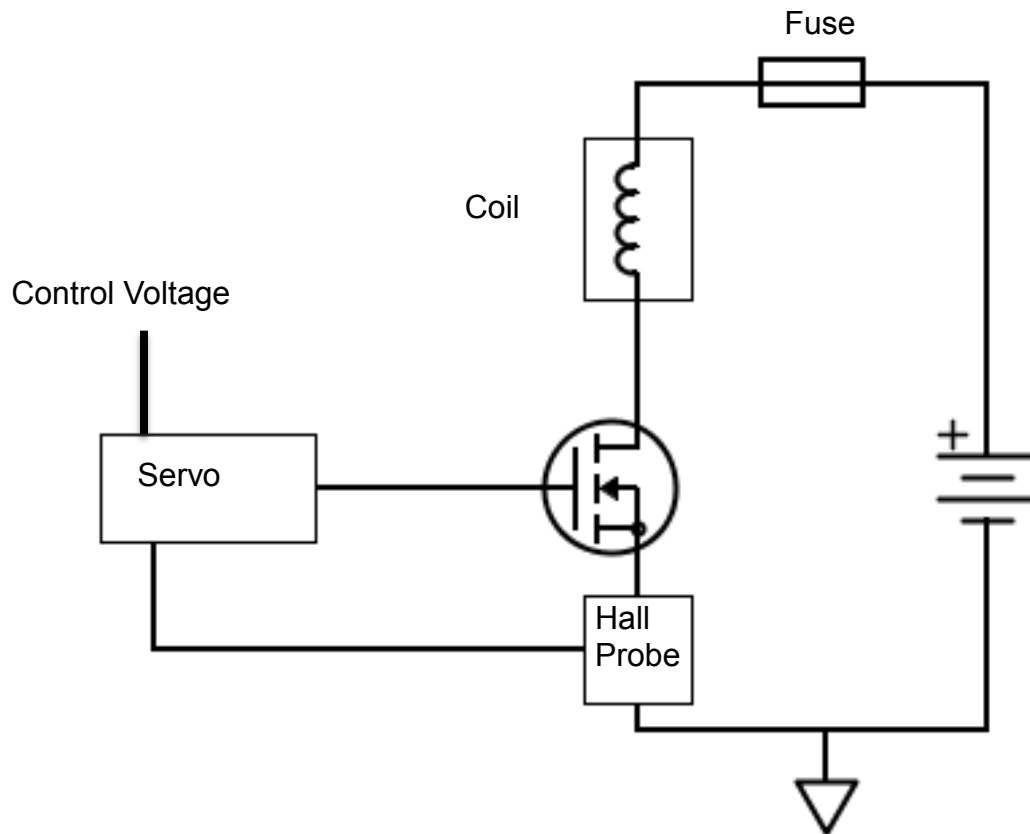


Figure 11: Schematic picture of circuitry used to drive the coils of the magnetic coil transfer system

The design of the servo circuits that will be used can be seen in Fig. 12 [5]. The signal from the hall probe is a voltage proportional to the current in the coils (see Fig. 13 for calibration of hall probe). The hall probe directly produces a current which is then connected to a resistor to

ground. The grounded edge of the resistor is connected to the resistor which is connected to the inverting terminal of the op-amp, while the other side of the resistor is connected to the resistor which is connected to the non-inverting terminal of the op amp. This voltage is then differentially amplified by the op amp to remove any noise.

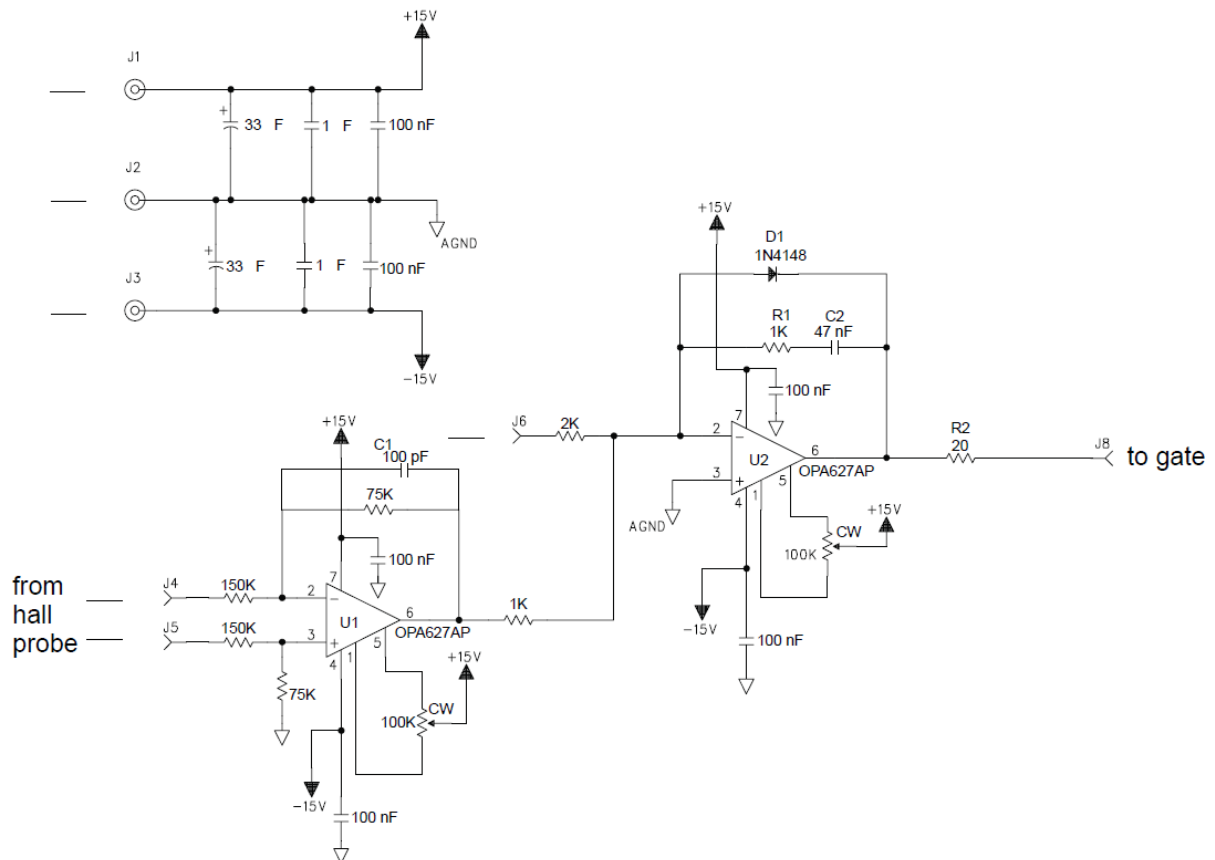


Figure 12: Servo circuit design

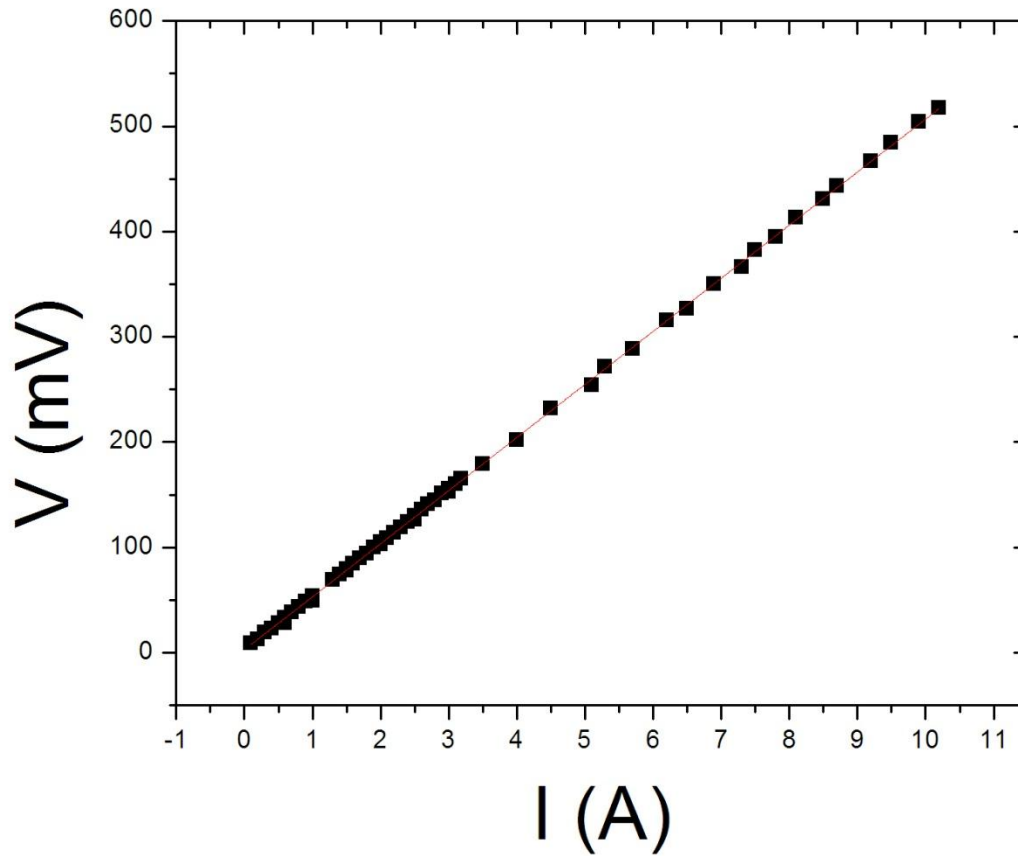


Figure 13: Output voltage of Hall probe assembly for a given input current. The displayed fit of the data is  $V = 2.97 \text{ mV} + I * 50.40 \text{ mV/A}$

The output of the differential amplifier is then compared with the control voltage and sent to the second op amp. This second op amp is an integrator; thus it gives high dc gain. The diode in the feedback clamps the output voltage at -0.6 V. This is simply to help protect the FET by preventing the possibility of driving it with a large negative voltage.



A measurement of the servo performance is the gain of the circuit as a function of the frequency of the input signal. This measurement was performed with and without a diode in parallel to the RC element of the feedback loop to see the diodes effect on the gain.

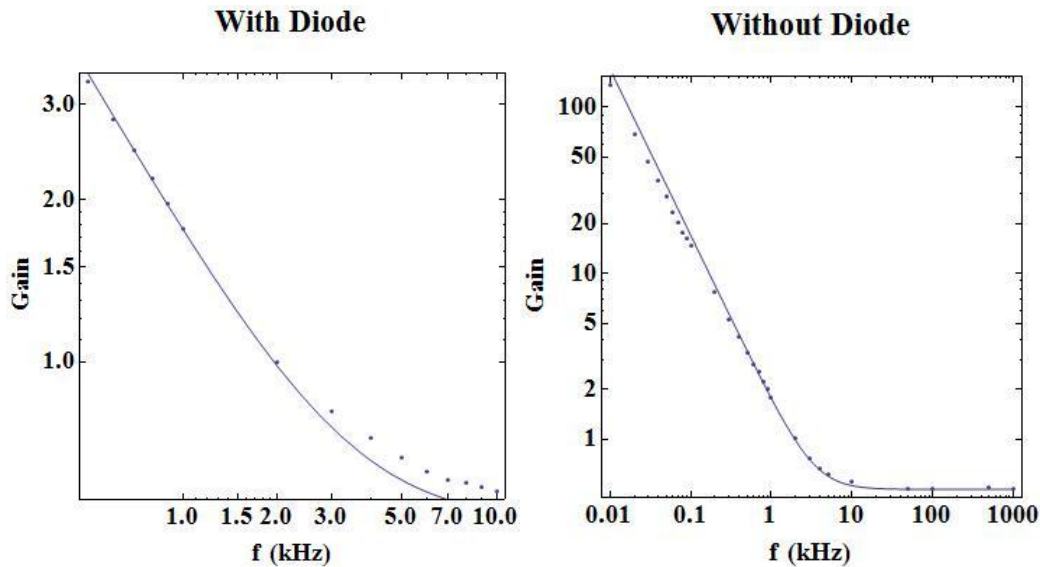


Figure 14: Gain of the servo as a function of the frequency of the input signal with and without a diode in the feedback loop. The curve plots the expected gain.

The curve on the plot shows the expected gain of

$$\frac{1}{2 k\Omega} \sqrt{(1 k\Omega)^2 + \left(\frac{1}{2\pi * f * 47 nF}\right)^2}$$

where  $f$  is the frequency of the signal. As can be seen from Fig. 9, the diode does not affect the gain significantly. We obtained much more data for the circuit without the diode, but the data for both situations match very closely.

The drain current of a FET is described differently depending on the voltages of the circuit. The FET is said to be in the linear region when  $V_{GS} > V_T$  and  $V_{DS} < (V_{GS} - V_T)$ . In this case, the drain current

$$I_D = 2K[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}]$$

When  $V_{GS} > V_T$  and  $V_{DS} > (V_{GS} - V_T)$ , the FET is said to be saturated and

$$I_D = K(V_{GS} - V_T)^2$$

where  $K$  is a temperature dependent coefficient,  $V_{GS}$  is the voltage from gate to source,  $V_{DS}$  is the voltage from drain to source, and  $V_T$  is the threshold voltage of the FET. We have been working in the saturation region by choosing a large  $V_{DS}$  and varying  $V_{GS}$  to control the current.

A measurement of the rise time of the servo and current was also performed. The response of the servo and the current in the coil to a 40 mV control voltage pulse can be seen in Fig. 15. The rise time of the servo was 13.8 ms while the rise time of the current was 6.6 ms. This is approximately the rise time we expect for the coil. Approximating the coil as an RL circuit, which has a time constant of

$$\tau = \frac{L}{R}$$

where we expect the inductance  $L$  to be on the order of a millihenry and the resistance  $R$  to be on the order of an ohm. This gives a time constant on the order of a millisecond.

The delay in the response of the current is due to the threshold voltage of the FET, which was measured to be 2.6 V. This windup can be removed either with the addition of an additional

stage of circuitry to raise the constant output voltage or by running a small constant current through the coils. The latter option is certainly unfavorable in the actual transfer process.

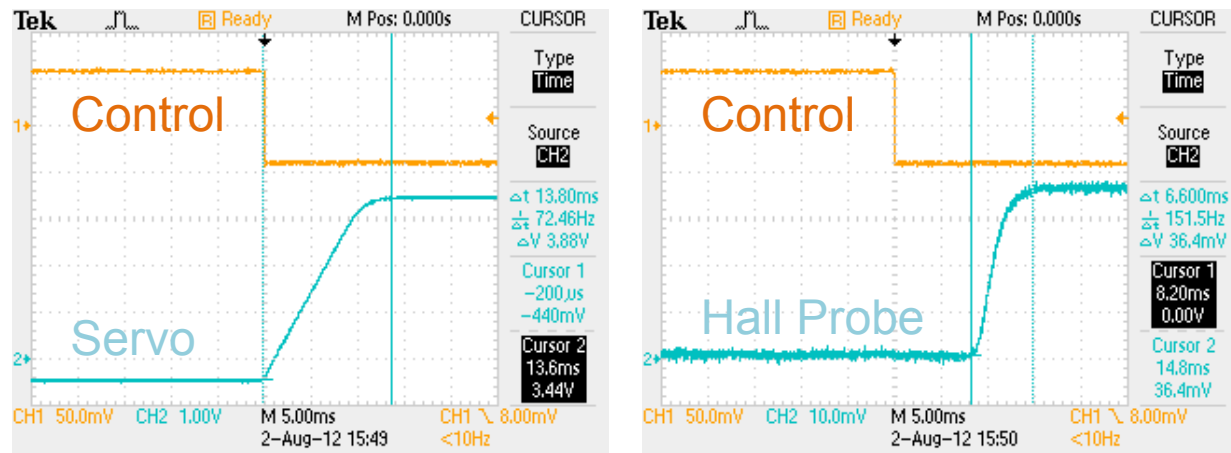


Figure 15: Rise time of servo and current in response to a 40 mV control voltage pulse

If there is a constant current running in the coils and the control voltage switches slowly, we expect the hall probe voltage to follow the control voltage. Due to the gains of the servo circuit, we expect that the hall probe voltage should be 1-1 with the control voltage. A check of this is shown in Fig. 16. The circuitry is able to exactly follow a 1 Hz triangle wave. We will be working with ramping currents, so it is good that the circuitry can follow a triangle wave.

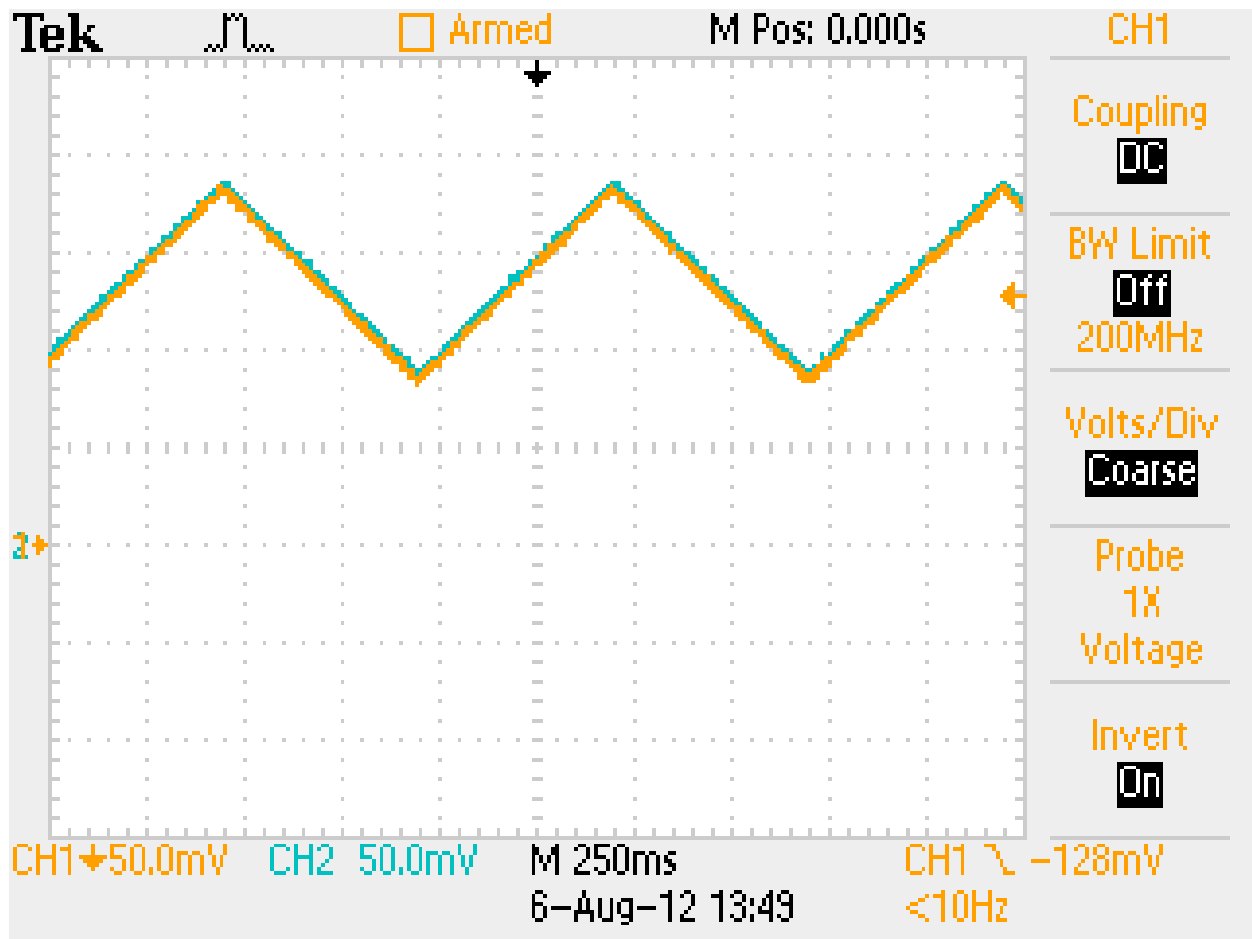


Figure 16: Hall probe voltage (in blue) following control voltage (in orange) in a 1-1 fashion

When testing the servo, we continually ran into the problem of the servo railing. This is because we initially were working with way too large of pulses for the power supply we were using. The working range of the servo is determined by the maximum current the power supply can drive; otherwise the servo will not get enough feedback and will rail.



Figure 17: Water cooled FET board

One final thing we made was a water cooled board to mount the FETs of the system onto. It was necessary to construct a thermally conductive board but have the FETs be electrically isolated. To do this, a silicon sheet is placed between the body of the FET and the board. Nylon bushings are also used to isolate the body from the 4-40 screws used to mount the FETs. Finally, thermal paste is added to increase the thermal conductivity between the FET and the board.

## 7 Conclusions

During this summer, we have made significant strides in developing the magnetic coil transfer system. For a given cloud temperature, we are now able to calculate the necessary trap depth and field gradients to capture the desired percentage of the atoms and have the cloud fit through the transfer tube. Given these calculated field gradients, we are able to solve the linear

system of equations for the currents in a system of three coils as a function of position to maintain these field gradients throughout the transfer process.

We also developed the backbone of the electronics system and have tested it to see that it should work very well for our purposes. The servo design is able to follow a control voltage on the timescale with which we will be working. Thus we should be able to drive the current in the coils with the needed degree of accuracy and stability to transfer the atoms with minimal heating.

## 8 Future Work

There is still much to be done in constructing the magnetic coil transfer system. One of the first major issues we need to address is the fact that we have a general solution for the steady transfer state. We need to convert the currents as a function of position to currents as a function of time by picking what maximum velocity we want for the atom cloud. We also need to decide how quickly we want to accelerate the atoms up to and back down from this maximum velocity. Essentially, this boils down to optimizing the transfer time to minimize heating of the atoms and atoms lost during the transfer process.

Another major concern is how to ramp up the field gradients. Initially the cloud is spherical when it resides within the MOT. During the transfer process the cloud is elongated along the transfer direction and compressed along the other two coordinates. We need to decide how quickly we want to transition between these two states.

We have developed the electronics to drive one coil pair but we will be working with on the order of ten coils. I have constructed three servos which may be enough if we share the

servos between coils using multiplexing. If we do any sort of switching, we have to be very careful that the current in the coil is zero when switching, otherwise we could cause sudden jolts in the trapping potential. We also need to develop the code to drive these coils with the correct voltage as a function of time to produce the desired current as a function of time.

Finally, we have to actually get the coils for the system and build it. The coils will exert a non-negligible force on each other, but epoxy should be enough to secure them. We need to develop a system to mount these coils along the transfer tube of the experiment.

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