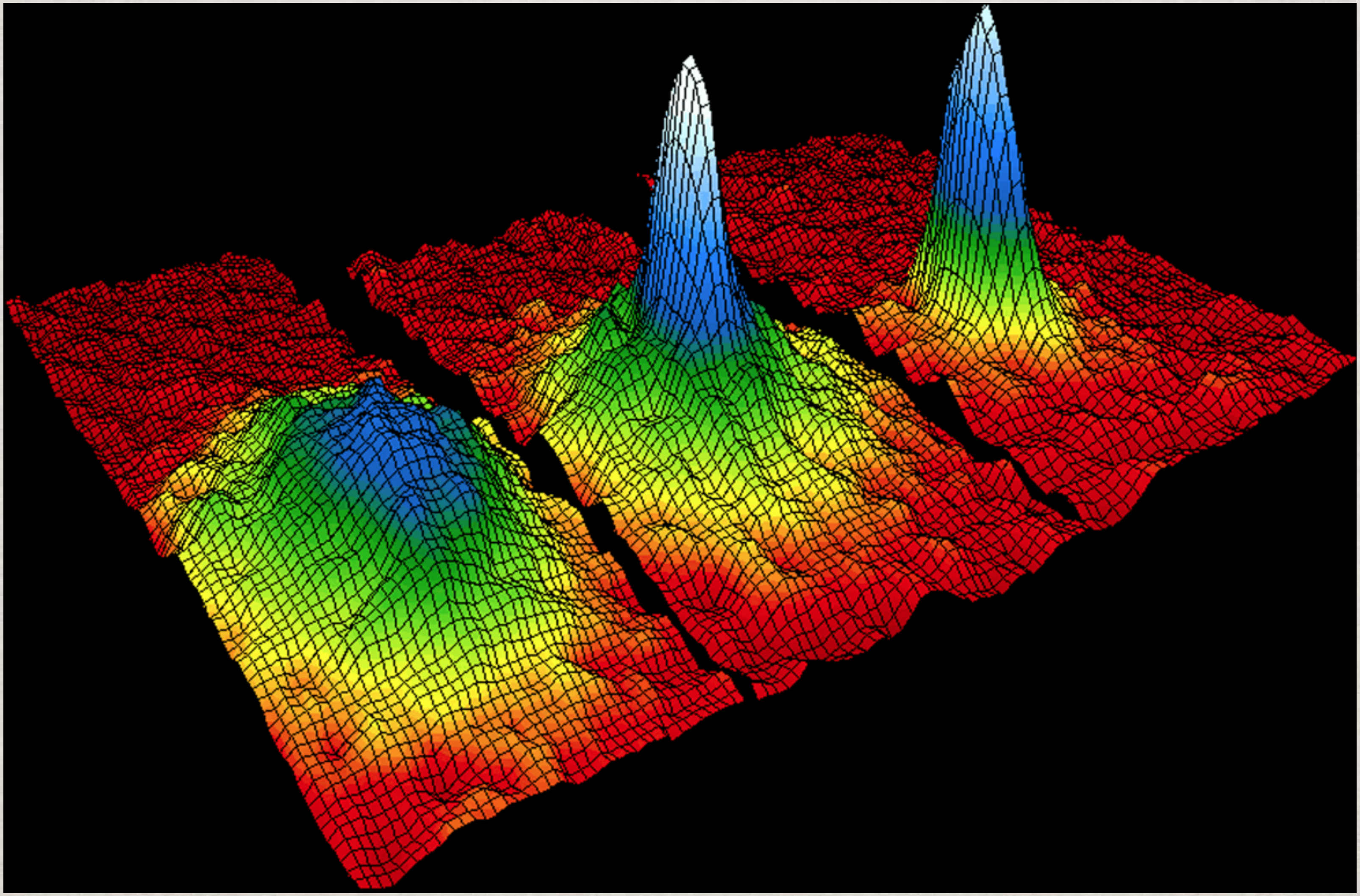
BEC’s and Me

Conrad Hawkins
Final REU Presentation

Bose-Einstein Condensates

- State of Matter
- Very near absolute zero (few billionths of a degree above absolute zero)
  - Coldest place in the universe!
- Wave-functions begin to overlap and particles become indistinguishable ($n\lambda > 2.6$)
- Predicted by Einstein and Bose in 1924
- Cornell and Wieman created first BEC in 1995 at Boulder

Rb-87 BEC



July 14th 1995 Boulder Group

The Lab

- The goal of the lab is to have ultra-cold Rb in a 2-D optical lattice w/ arbitrary potentials within a year
- Optical arbitrary potentials are better to make configurations (harder to get running, easier to change)
  - Move really cold particles around easily
- 2-D physics is fun
  - Fractional quantum Hall effect
  - Model transistor gates at small scales

My Summer Project

- Increase my understanding of ultra-cold physics
- Work on various projects in order to optimize the apparatus
- Housekeeping
- Not doing anything specific

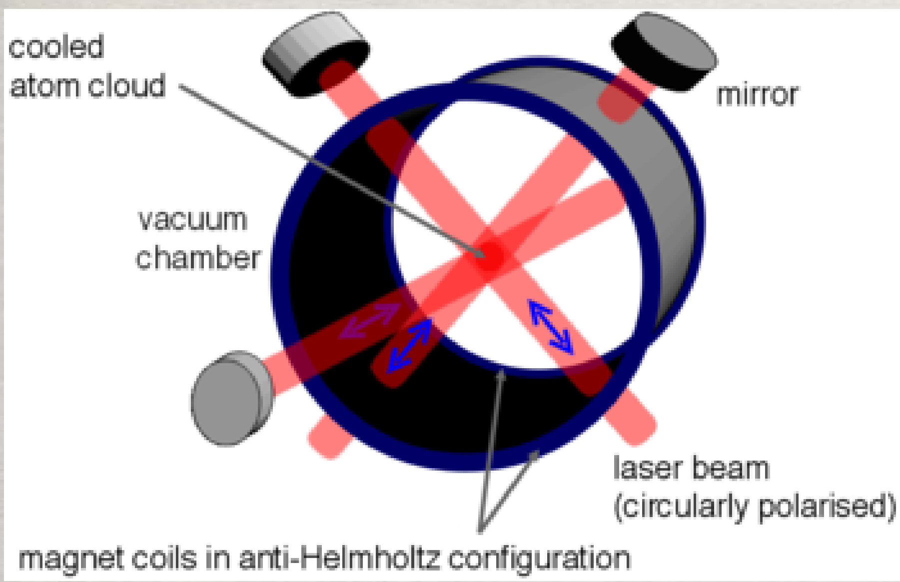
BEC Techniques

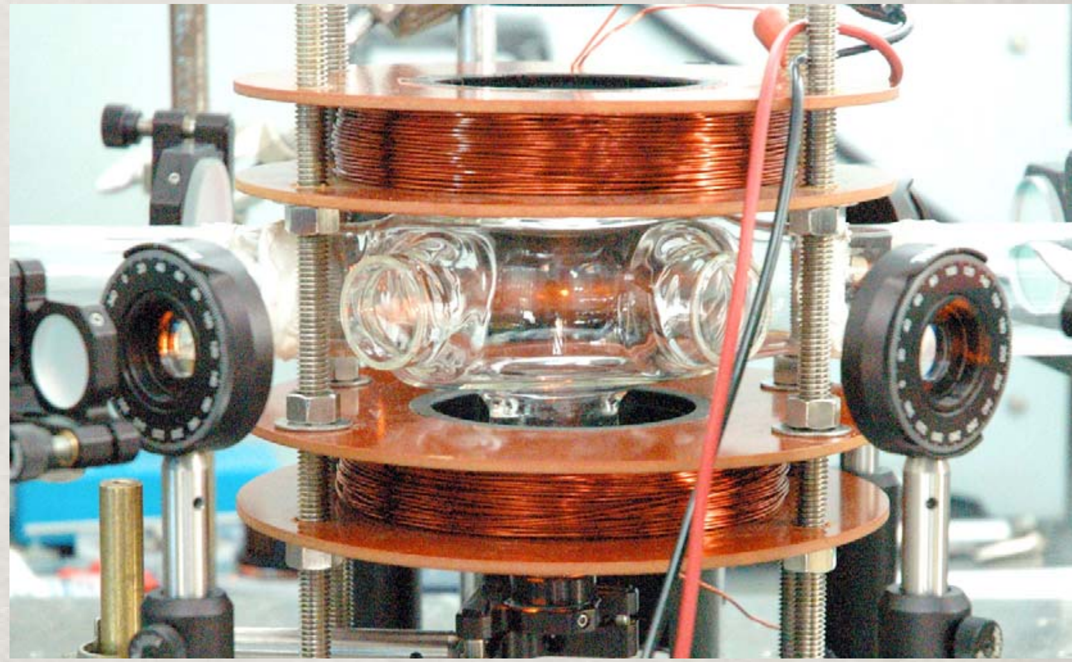
- Two steps used in order to make a BEC
  - Laser cooling
  - Evaporative cooling

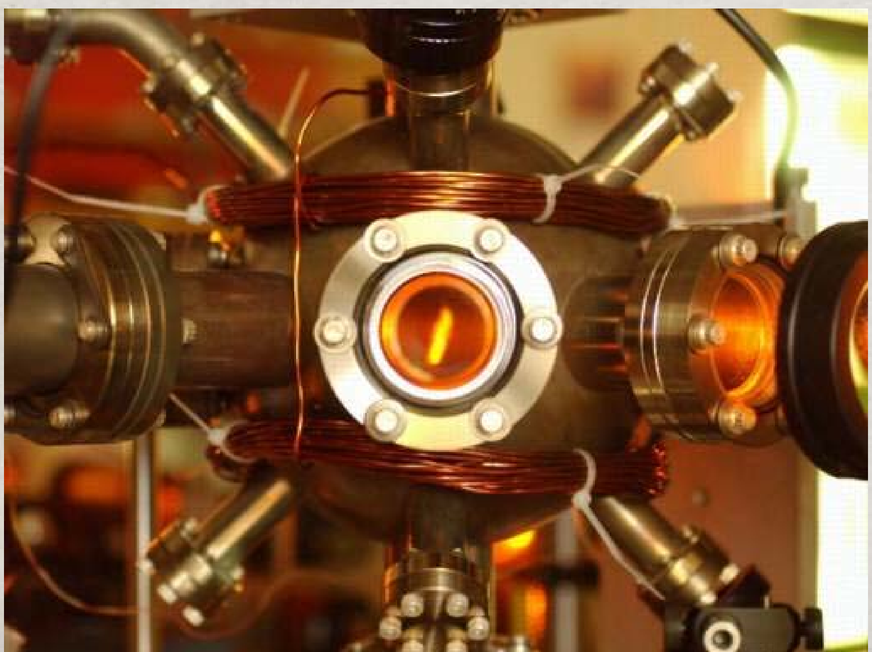
Magneto-Optical Trap

- Photons impart a momentum equal to $\hbar k$ to an atom before absorption
- Using the doppler shift one can allow light to only be absorbed if it heads toward the laser source (red detuned)
- Using magnetic trap (quadrupole coils) can shift spectral line in a radial direction
    - More likely to get pushed toward center of trap

MOT Pictures







MOTs cools to μK regime

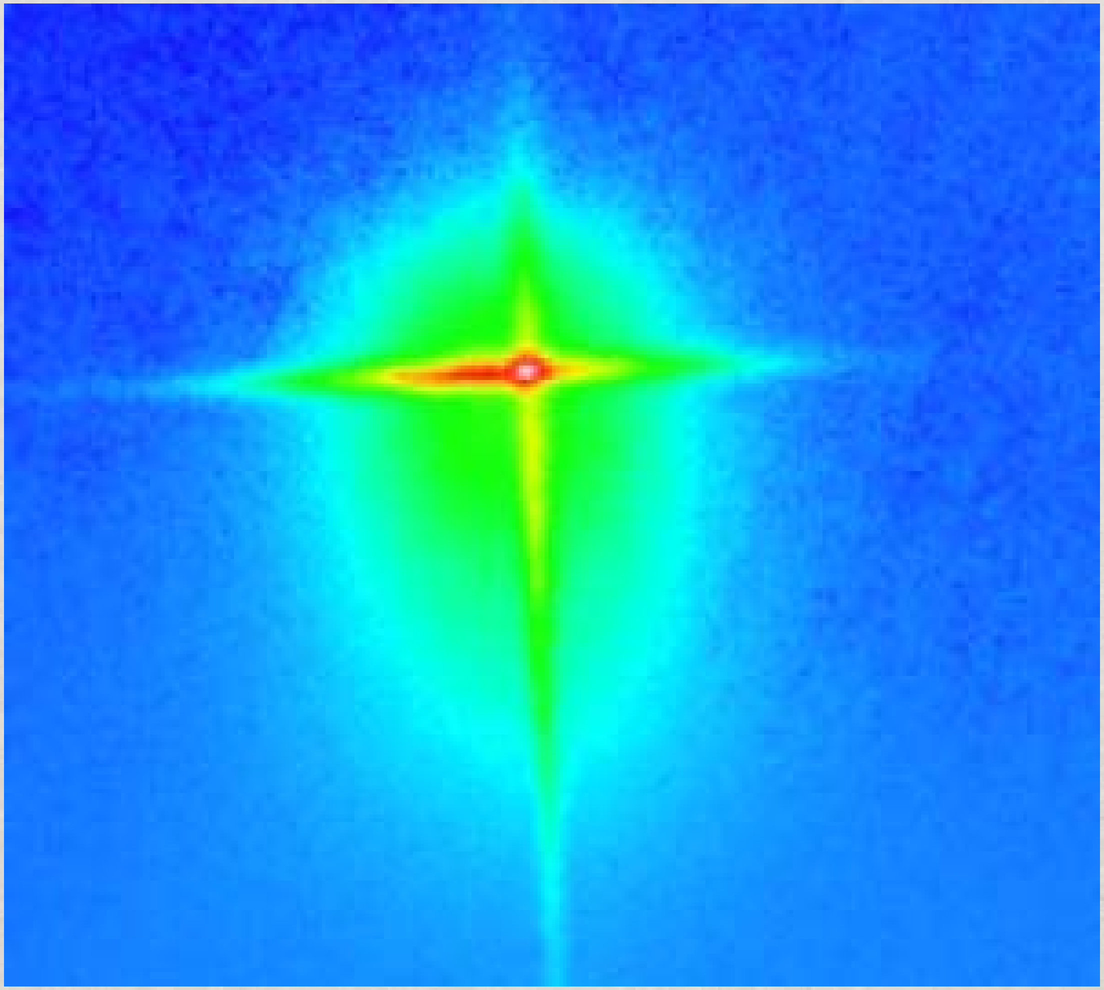
Evaporative Cooling

- We use a cross-beam dipole trap in order to achieve evaporative cooling
- Laser beam shifts energy levels of the atoms due to Stark effect and induces dipole moments
- Atoms attracted to higher laser intensity if red-detuned (traps atoms in beam)
- Slowly decrease laser intensity to decrease temperature

Coffee Cup Analogy

- Hottest particles escape from the cup as steam
- Lower the walls of the trap (decreasing intensity of beam)
- Left with cold molecules

Cross-Beam Dipole Trap



Atoms pulled to the crossing of the optical beams

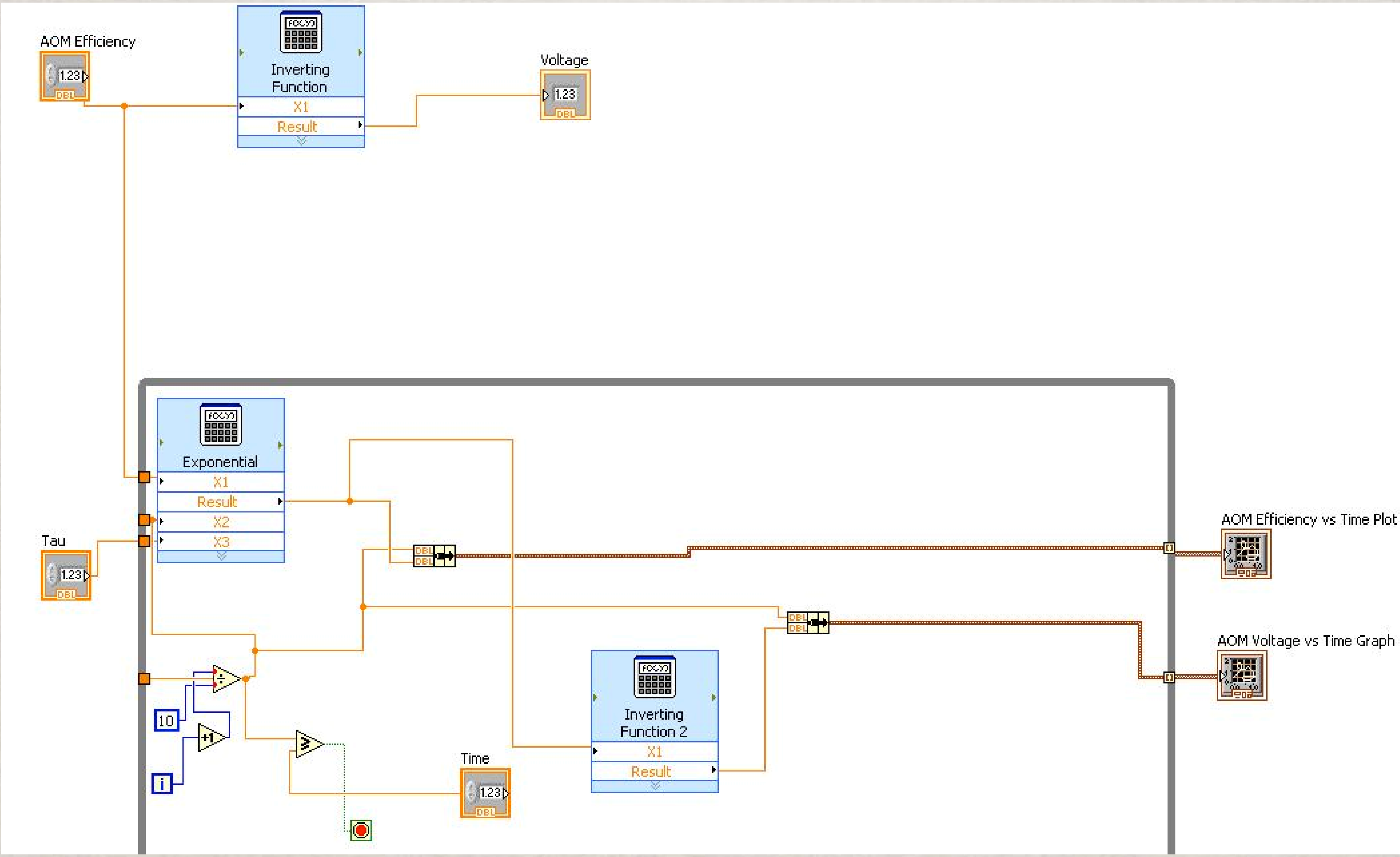
Acousto-optic modulator (AOM)

- An incoming beam is split into two ordered beams. The zero ordered diffraction passes right through the AOM undeflected, but the first order diffraction beam is deflected at a certain angle
- By applying a certain voltage to the AOM through a computer one can vary the intensity of the diffracted beam
- Useful as an on/off switch and changing frequency

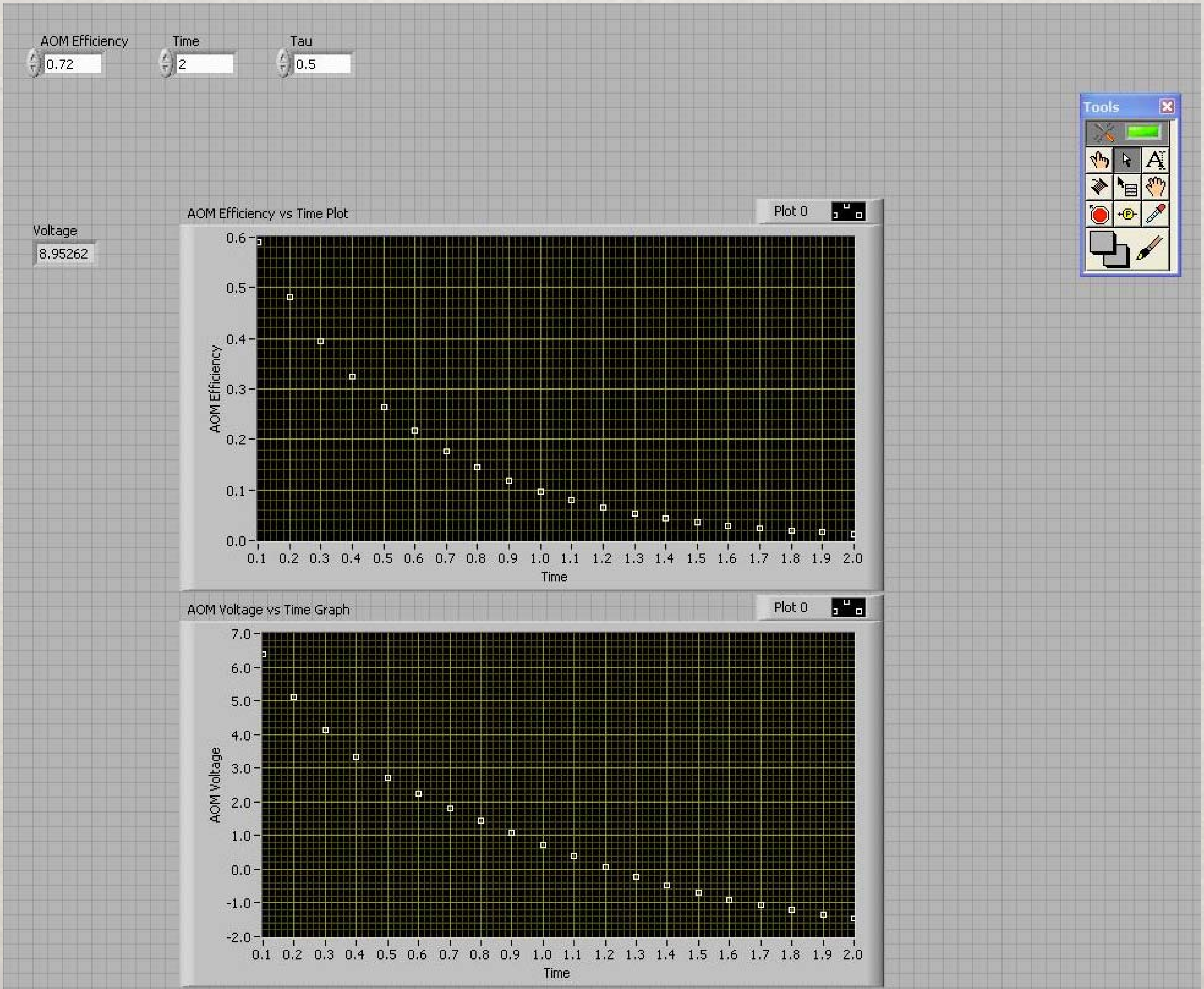
Project #1

- Calculated parameters for an AOM so first order beam has an exponential decay
  - Calibrated using LabView and experimental measurements
  - Wrote program which displays output voltage, efficiency vs time plot, and volt vs time plot for a given efficiency

LabView Code Block



LabView Code Front



Project 2

- Modeling dipole trap capturing MOT atoms in free-fall
- Given various parameters will an atom from the MOT get collected into the dipole trap
- 3 Interactions to consider:
  - Gravity
  - Dipole Trap Potential
  - Particle collisions (random collisions where force is determined by Boltzmann distribution)
- Not much research has been done on capturing the MOT atoms into the dipole trap
  - People are mostly trying to optimize it by hand instead of running computer simulations

MatLab Code 1

Editor - /Users/chawkins/Documents/MATLAB/maxwelltrap.m

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```
clear all
syms x y z w a b
for i = 0:0
    %constants
    permE = 8.854*10^-12; %permitivity of free space
    c = 2.9979*10^8; %speed of light
    cE=1.602*10^-19; %charge of electron
    mE=9.109*10^-31; %mass of electron
    omega0= 2 * pi*c/(780*10^-9); %D2 line of Rb
    gamma= 36.13*10^6; %Rb D2 transition, from Steck
    mRb = 87*1.672*10^-27; %mass of Rb87
    hbar = 1.0546*10^-34;
    a0=.529*10^-10; %bohr radius

    daWaist=2e-4;
    daPower= 45;
    daWavelength=1550*10^-9;
    U0 = 2*daPower*((-3*pi*c^2 * gamma)/(pi*daWaist^2 * 2 * omega0^3))*(1
    deltat = .00018; %in seconds
    beam_waist = daWaist;
    pmass = mRb;
    zr = pi* beam_waist^2/daWavelength;
    g = 9.8;
    endtime = .01;

    %cross trap angle
    thetadeg = 90;
    theta = (thetadeg*pi)/180;
    a = x*cos(theta) + z*sin(theta); %x direction with theta
    b = -x*sin(theta) + z*cos(theta); %z direction with theta

    %Maxwell boltz dist constants
    kb = 1.38*10^-23; %Boltzmans Constant
    T = 100e-6; %Kelvin
    deltaw = .005;
    endw = .4;
    numberdensity = 10^8/((4/3)*pi*(1e-3/2)^3); %10^8 atoms over 1mm widt
    Rbdiameter = 112*a0*2; %times by 2 to get diameter

    %Photon absorb constants

    deltag = 30e6; %30 megahertz
    m0 = (hbar*2*pi)*3.412341305452145*1e6; %Steck S-state data convertec
    omega1 = 2*pi*c/daWavelength;
    dagamma = (omega1^3*m0^2)/(3*pi*permE*hbar*c^3);
    datau = 1/dagamma;
    Is = (pi*(hbar*2*pi)*c)/(3*daWavelength^3*datau);
    s0 = daPower/Is;
    wavek = 2*pi/daWavelength;
    beta = (-1*hbar*wavek^2)*((8*s0*(deltag/dagamma))/(1+(2*deltag/dagamm

    %potential energies (divided by mass)
    Utrap = (-1*(U0/(1+(b/zr)^2))*exp((-2*a^2-2*y^2)/(beam_waist^2*(1+(b/

    Utrap_z = diff(Utrap,z);
    Utrap_y = diff(Utrap,y);
    Utrap_x = diff(Utrap,x);

    %initial values
    z1 = 0;
    y1 = .5e-4; %does not escape from here
    %y1 = 1e-2; %escapes from here
    x1 = 0;
```

script | Ln 1 | Col 1

Editor - /Users/chawkins/Documents/MATLAB/maxwelltrap.m*

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```
    %Graphing
    time = 0:deltat:endtime;
    ypos = [y1];

    %Find initial potential energy due from dipole trap and gravity
    U_plugx = subs(Utrap,x,x1);
    U_plugz = subs(U_plugx,z,z1);
    U_plugy = subs(U_plugz,y,y1);

    %maxwell-boltz dist (w = velocity)
    fw1 = (1)*sqrt((2/pi)*(pmass/kb*T)^3)*w^2*exp((-pmass*w^2)/(2*kb*T));
    norm = int(fw1,-inf,inf);
    fw = (1/norm)*sqrt((2/pi)*(pmass/kb*T)^3)*w^2*exp((-pmass*w^2)/(2*kb*

%     figure;
%     ezplot(fw,[0,.4]); %Plots maxwell-boltz dist;
%     xlabel('Velocity (m/s)');
%     ylabel('Probability Density');
%     title('Maxwell-Boltzmann Distribution')


    %generate weighted list with all maxwell boltz speeds
    w1 = 0; %stars w values here
    wval = 0:deltaw:endw; %list of all w values

    for a = 0:deltaw:endw
        w2 = w1;
        fwi = [subs(fw,w,w2)];
        fwval(floor(a/deltaw)+1) = fwi; %makes list of all f(w) values
        w1 = w2 + deltaw;
    end

    for b = 1:numel(fwval)
        numberoftimes = int32(fwval(b)*wval(b)*100); %100 from 1e14
        numberoftimesvector(b) = numberoftimes; %list of # of times each
    end

    shift = 0;
    listofspeed = [];

    for c = 1:numel(numberoftimesvector)
        for d = 1:numberoftimesvector(c)
            listofspeed(d+shift) = wval(c); %puts all speeds in big list.
        end
        shift = numel(listofspeed);
    end

    %Probability that 2 atoms collide
    collisionfreq = numberdensity*sqrt(2)*pi*Rbdiameter^2*sqrt((8*kb*T)/(
    p2atoms = deltat*collisionfreq;


    %set initial velocities based off boltzmann distribution
    rand('seed',sum(100*clock)) %reseed random number generator for initi

    the_lucky_number = floor(numel(listofspeed)*rand(1)-.1); %picks rando
    speed = listofspeed(the_lucky_number);

    velxpos = speed/sqrt(3);
    velypos = speed/sqrt(3);
    velzpos = speed/sqrt(3);

    if rand(1) > .5;
```

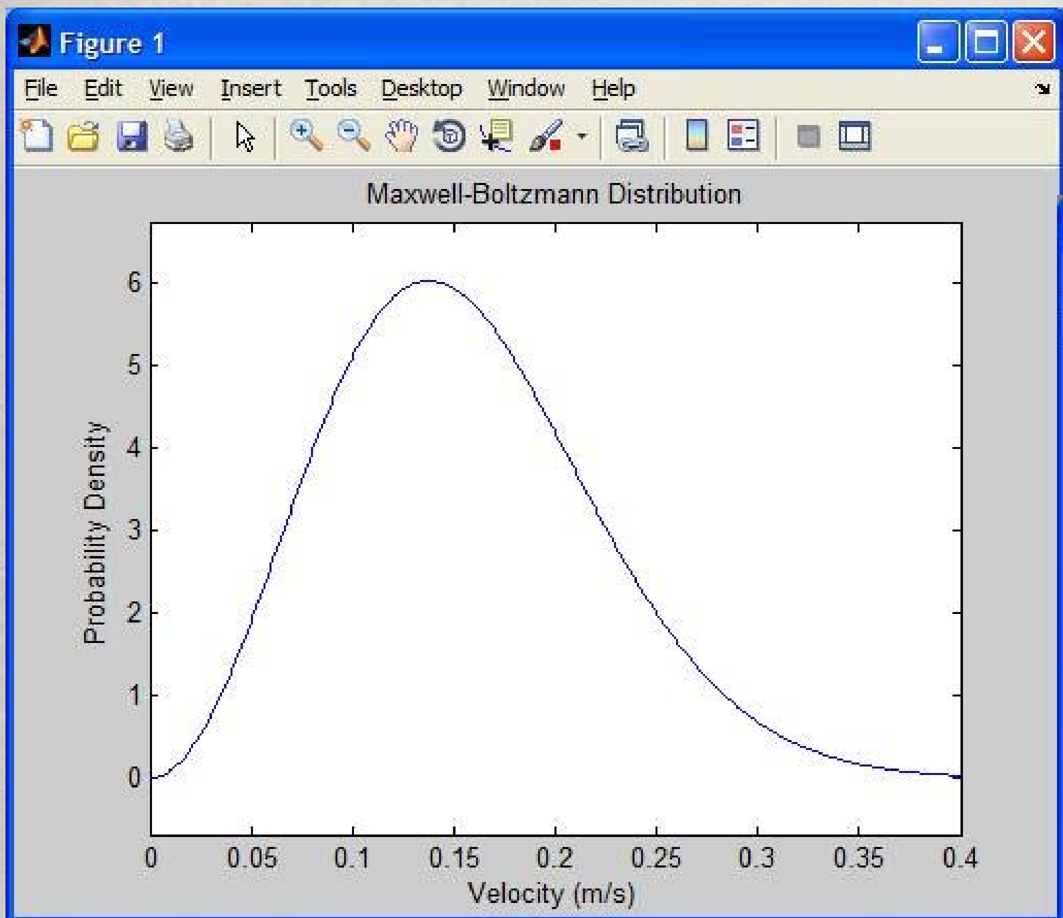
script | Ln 26 | Col 22

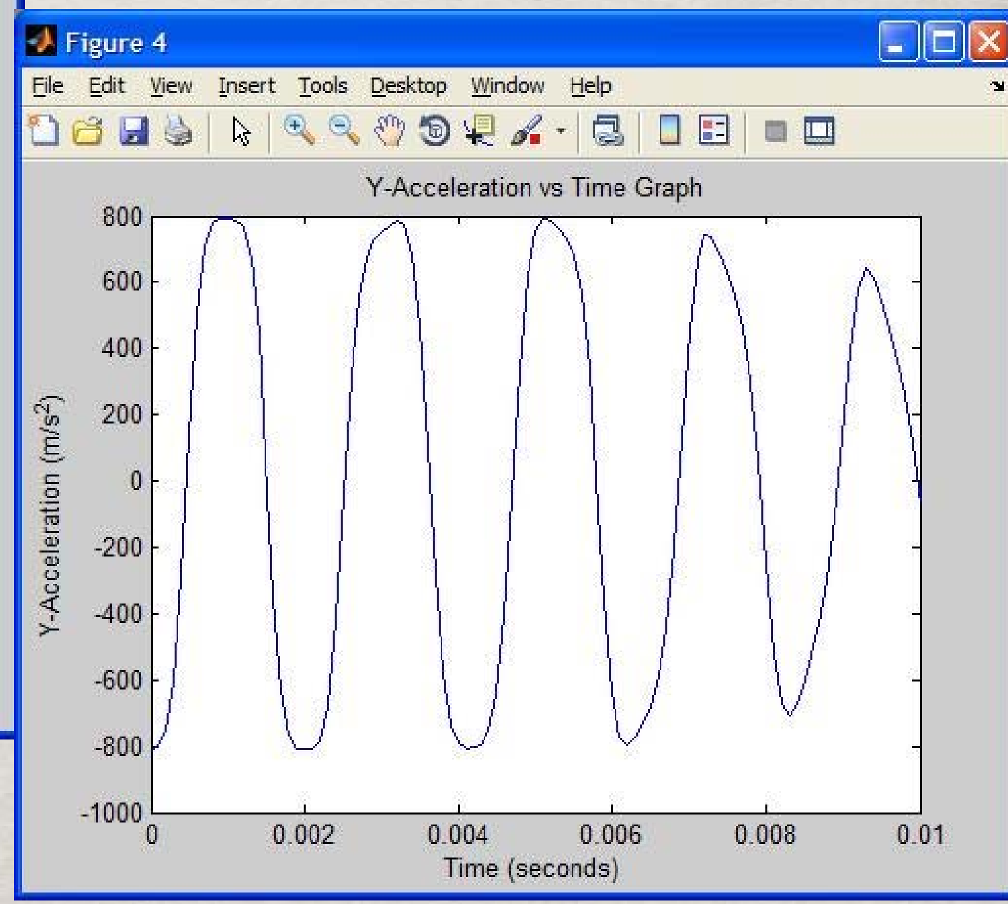
MatLab Code 2

```
        if rand(1) > .5;
            vx = -1*velxpos;
        else
            vx = velxpos;
        end

        if rand(1) > .5;
            vy = -1*velypos;
        else
            vy = velypos;
        end

        if rand(1) > .5;
            vz = -1*velzpos;
        else
            vz = velzpos;
        end

        updateStep=1;

        %Force/vel/pos equations
        for i = 0:deltat:endtime
            rand('seed',sum(100*clock)) %reseed random number generator each

            Utrap_z1 = subs(Utrap_z,x,x1); %Plug in for x-y values to find a_
            Utrap_z2 = subs(Utrap_z1,y,y1);
            a_z = subs(Utrap_z2,z,z1)+((beta*vz)/pmass);

            Utrap_y1 = subs(Utrap_y,x,x1); %Plug in for x-z values to find a_
            Utrap_y2 = subs(Utrap_y1,z,z1);
            a_y = subs(Utrap_y2,y,y1)-g+((beta*vy)/pmass)

            Utrap_x1 = subs(Utrap_x,y,y1); %Plug in for y-z values to find a_
            Utrap_x2 = subs(Utrap_x1,z,z1);
            a_x = subs(Utrap_x2,x,x1)+((beta*vx)/pmass);

            vz1 = vz + a_z*deltat; %Update velocity
            vy1 = vy + a_y*deltat;
            vx1 = vx + a_x*deltat;

            z2 = z1 + vz1*deltat; %Update position
            y2 = y1 + vy1*deltat;
            x2 = x1 + vx1*deltat;

            ypos(updateStep) = y2; %append value to list to graph
            vypos(updateStep) = vy1;
            aypos(updateStep) = a_y;
            xpos(updateStep) = x2;
            zpos(updateStep) = z2;

            %Probabilistic collision of 2 atoms

            if rand(1) < p2atoms
                %%picks a number from the list of speeds a particle has giver
                %%maxwellboltz dist and then turns it into a velocity

                the_lucky_number = floor(numel(listofspeed)*rand(1)-.1); %pic

                speed = listofspeed(the_lucky_number);

                velxpos = speed/sqrt(3);
                velypos = speed/sqrt(3);
                velzpos = speed/sqrt(3);
```

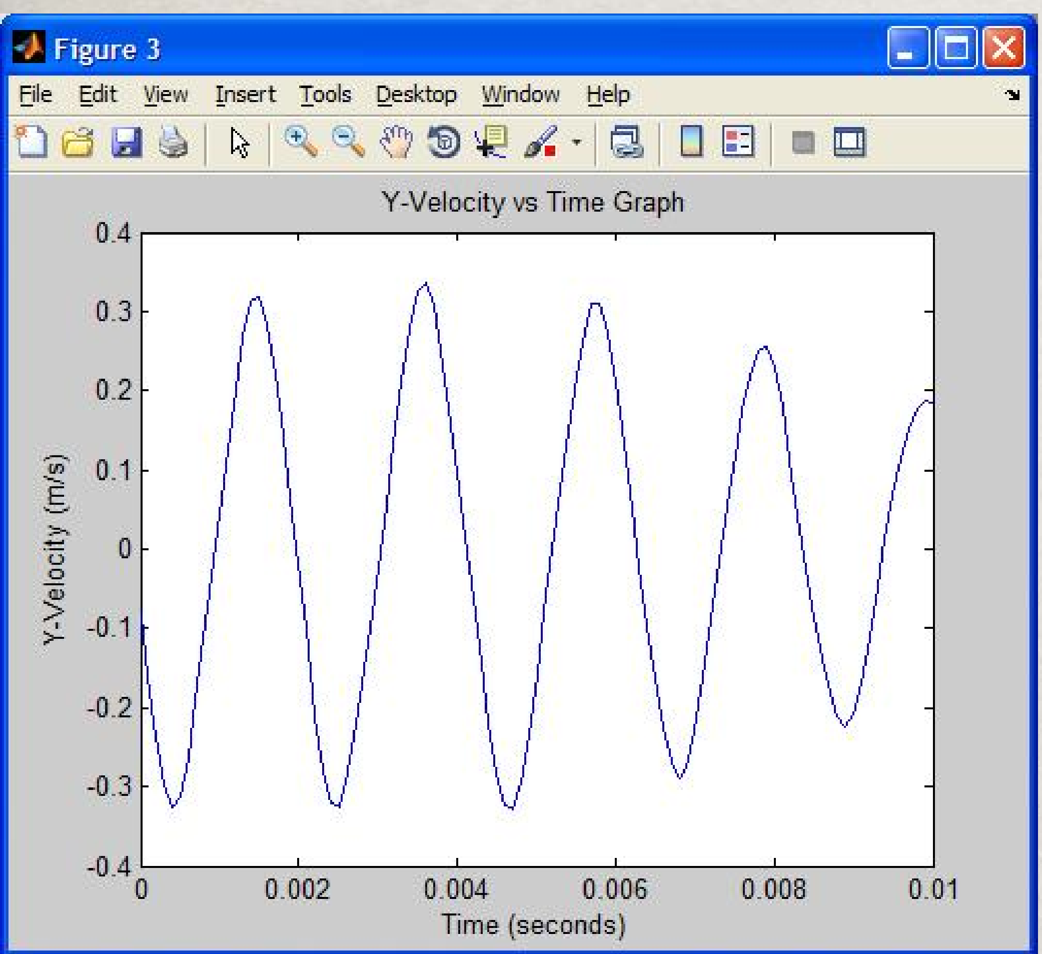
```
                velzpos = speed/sqrt(3);

                if rand(1) > .5;
                    velx = -1*velxpos;
                else
                    velx = velxpos;
                end

                if rand(1) > .5;
                    vely = -1*velypos;
                else
                    vely = velypos;
                end

                if rand(1) > .5;
                    velz = -1*velzpos;
                else
                    velz = velzpos;
                end
                %velx,vely,velz is the random particles velocity

                vx = velx; %collided so takes random particles velocity
                vy = vely;
                vz = velz;
            else
                vx = vx1; %did not collide so updates old velocity
                vy = vy1;
                vz = vz1;
            end


            z1 = z2; %Save new position
            y1 = y2;
            x1 = x2;
            updateStep = updateStep +1;
        end

        figure(2);
        plot(time,ypos);
        xlabel('Time (seconds)');
        ylabel('Y-Position (meters)');
        title('Y-Positions vs Time Graph')

        figure(3);
        plot(time,vypos);
        xlabel('Time (seconds)');
        ylabel('Y-Velocity (m/s)');
        title('Y-Velocity vs Time Graph')
%
%         figure(4);
%         plot(time,aypos);
%         xlabel('Time (seconds)');
%         ylabel('Y-Acceleration (m/s^2)');
%         title('Y-Acceleration vs Time Graph')

        figure(5);
        plot3(xpos,ypos,zpos,'d')
        xlabel('X-position (meters)')
        ylabel('Y-position (meters)')
        zlabel('Z-position (meters)')

        y1
    end
```

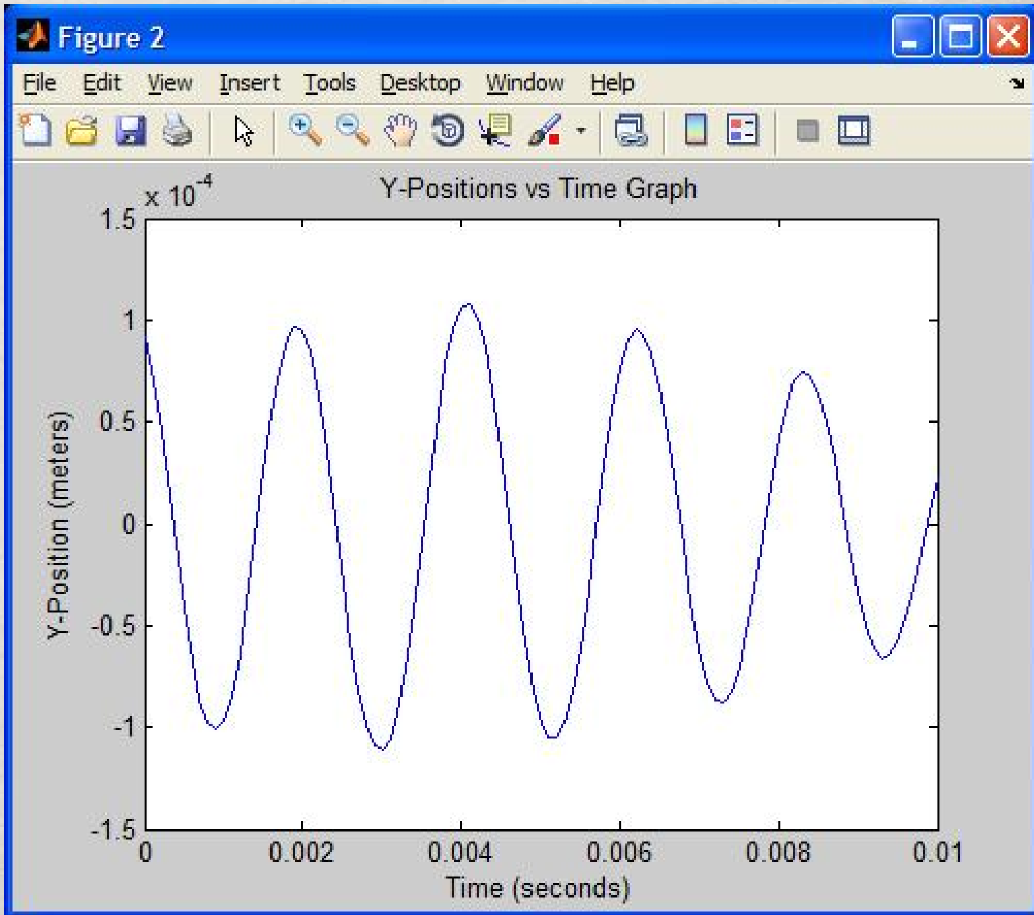
MatLab Output 1





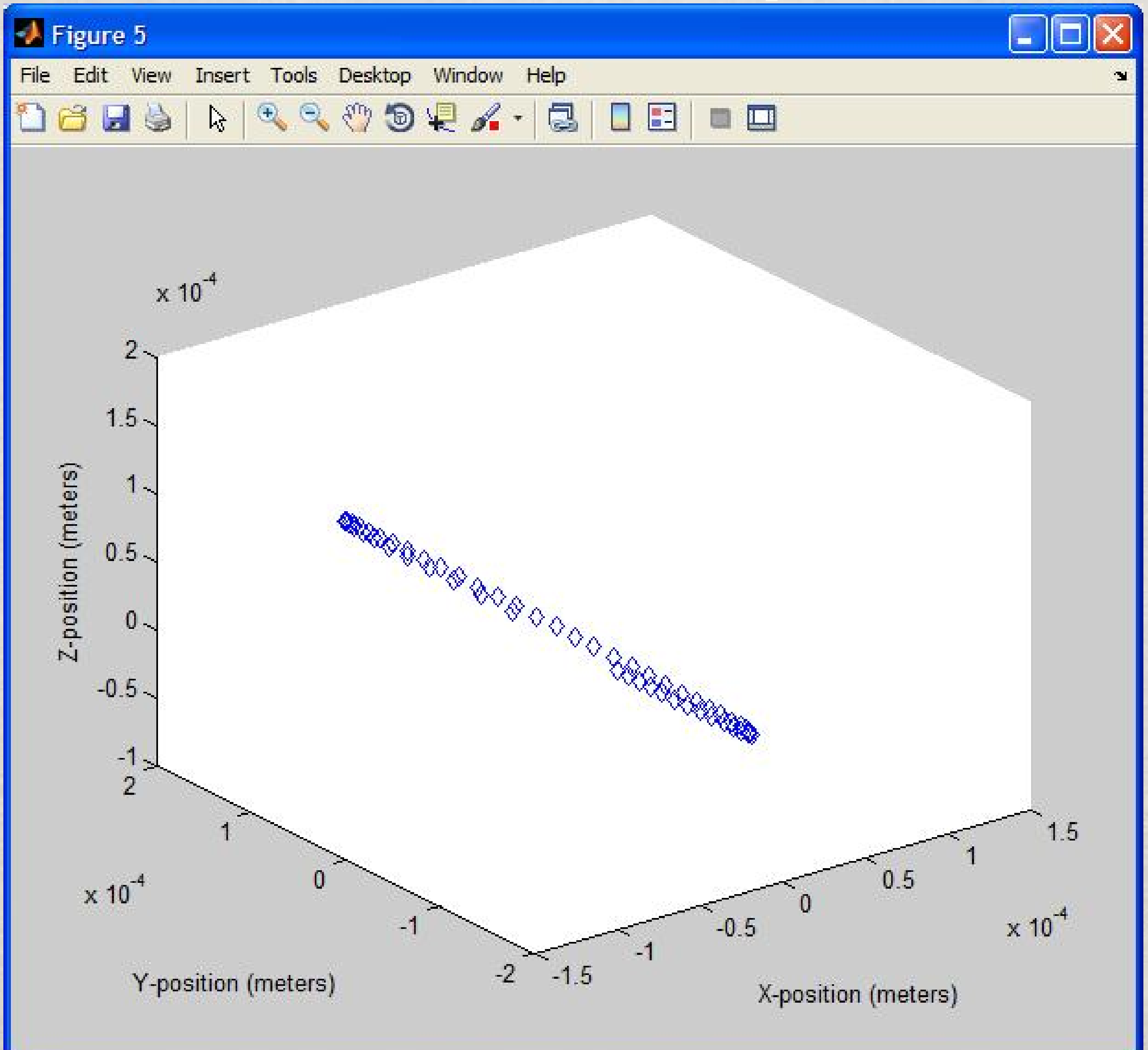
MatLab Output 2





Particle gets stuck!

Matlab output 3



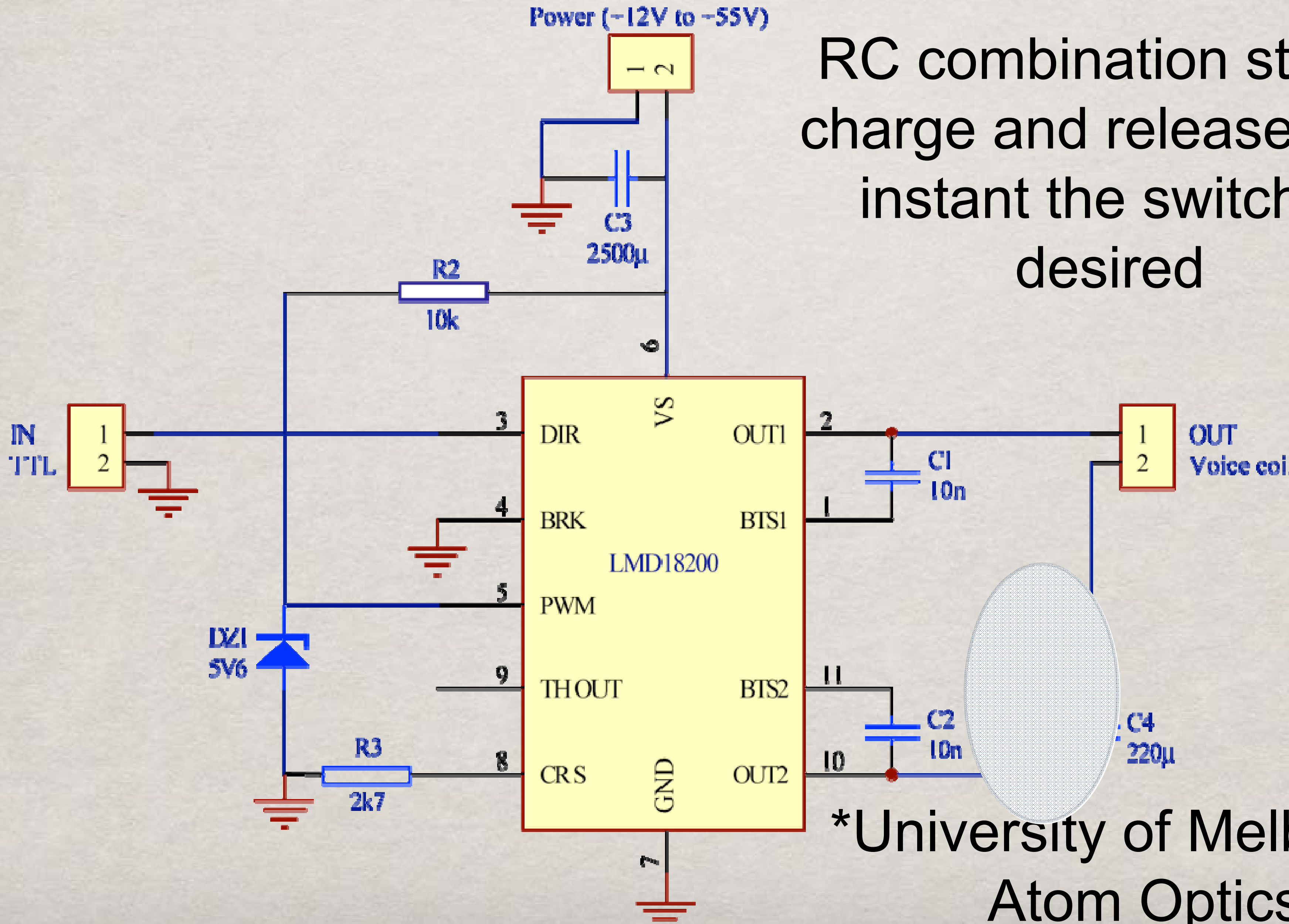
Project 3

- The light shutters used in the lab open/close on the millisecond scale
- Need to open/close it faster (something on the microsecond scale)
- Building a light shutter that can hopefully open/close at .5 microseconds

Hard Drive Shutter

- Building shutter out of a hard drive
- HD arm moves very quickly
- Attaching circuit to voice coil will allow control of arm

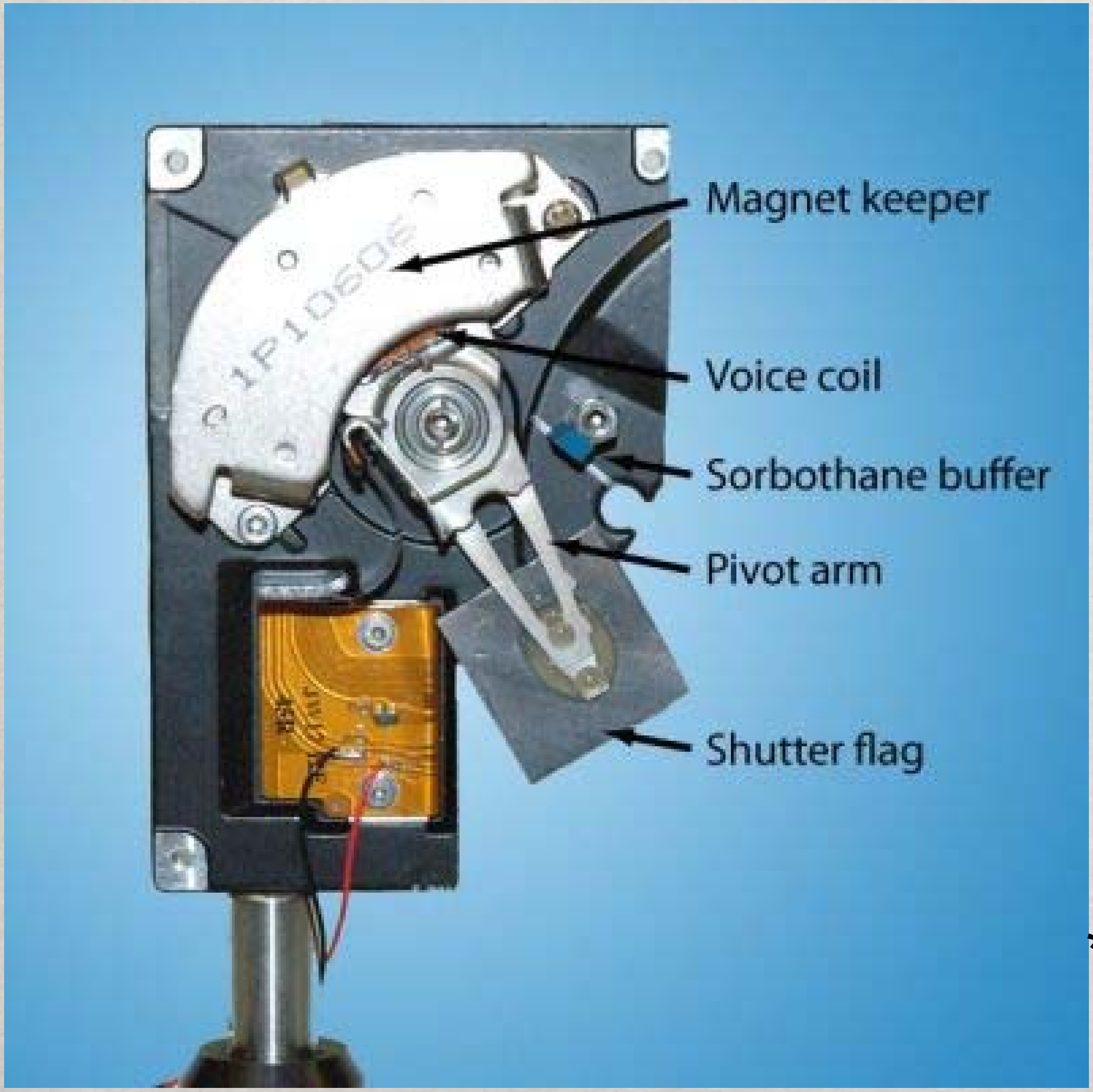
Shutter Circuit



RC combination stores charge and releases the instant the switch is desired

*University of Melbourne Atom Optics

Finished Product



*University of Melbourne Atom Optics

Hard Drive Progress

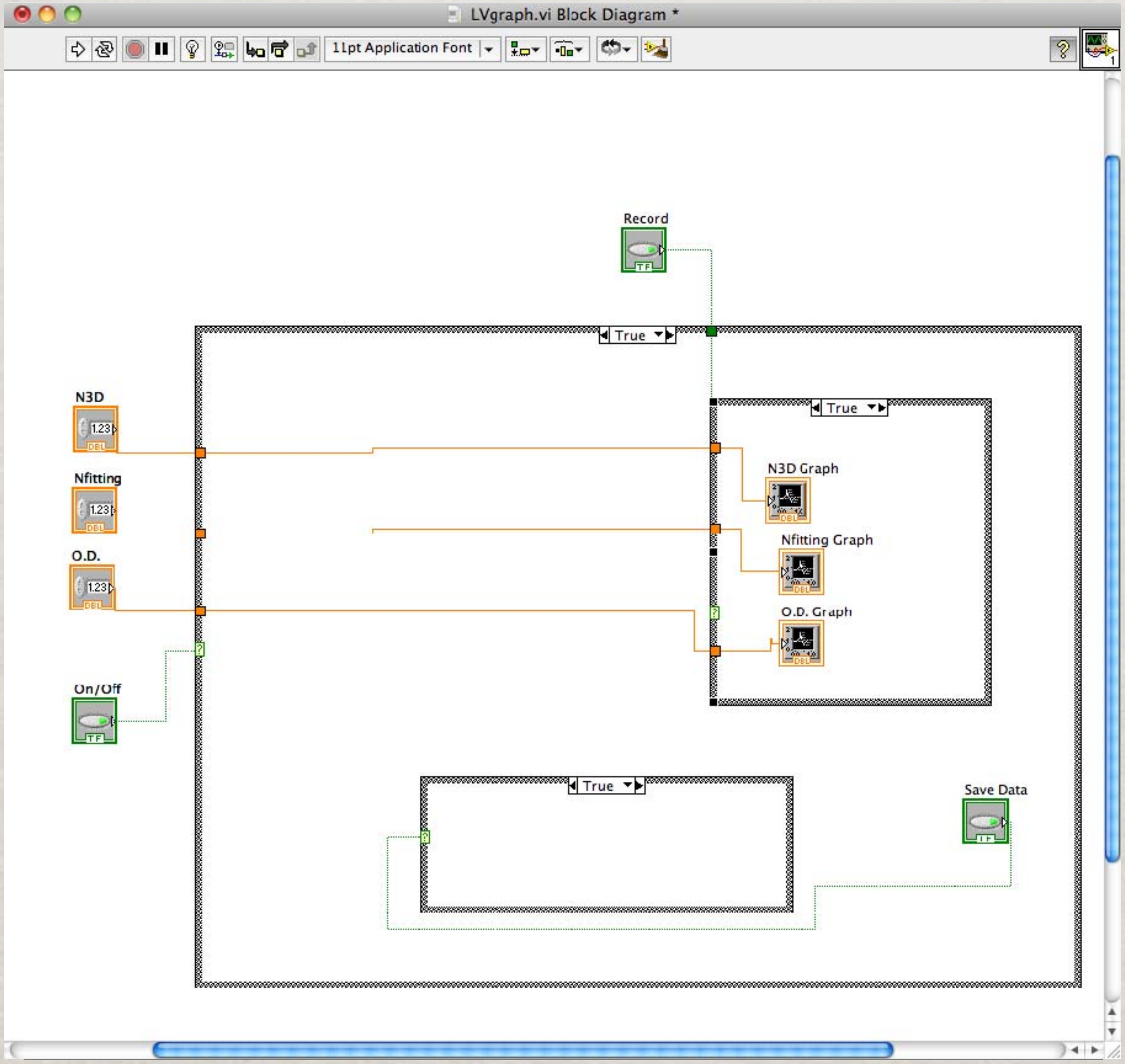
- Soldered the circuit to PCB board
- Created an enclosure for the circuit
- Had everything tested and working, until I broke it
- I fried the IC and am currently waiting for new ones

HD Shutter

Project 4

- Created a program in LabView that allowed live updates of 3 parameters and graphed them instantaneously
- The input parameters were O.D., N3D, and Nfitting
- The output is 3 graphs

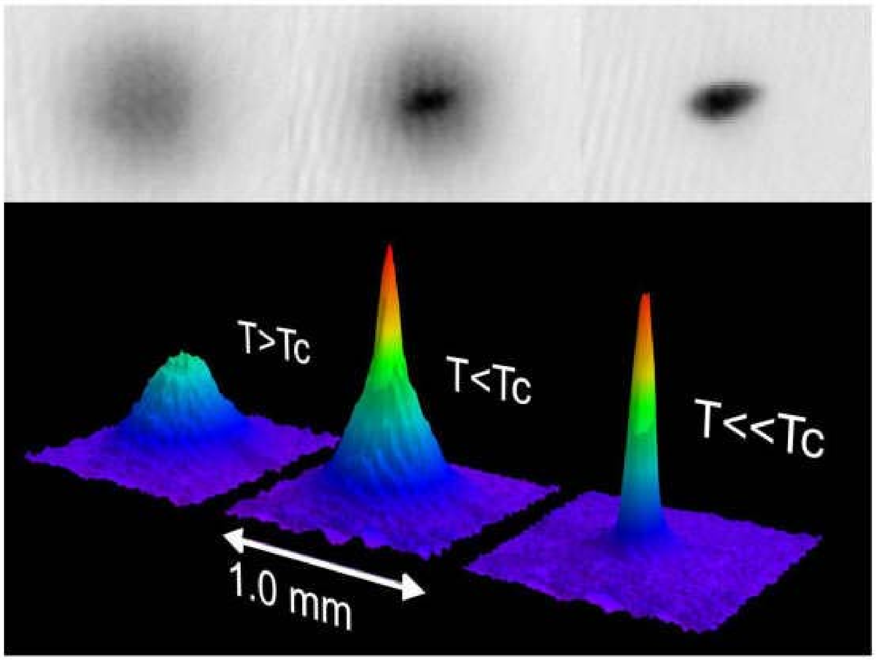
LabView Code



Project 5

- Created LabView program that created a line of best fit for Bose-Einstein condensates
- During the transition to a BEC the particle distribution changes from a Gaussian distribution to a Thomas-Fermi distribution

Thomas-Fermi Distribution



Coherent Spin Dynamics of a Spin-1 Bose-Einstein Condensate

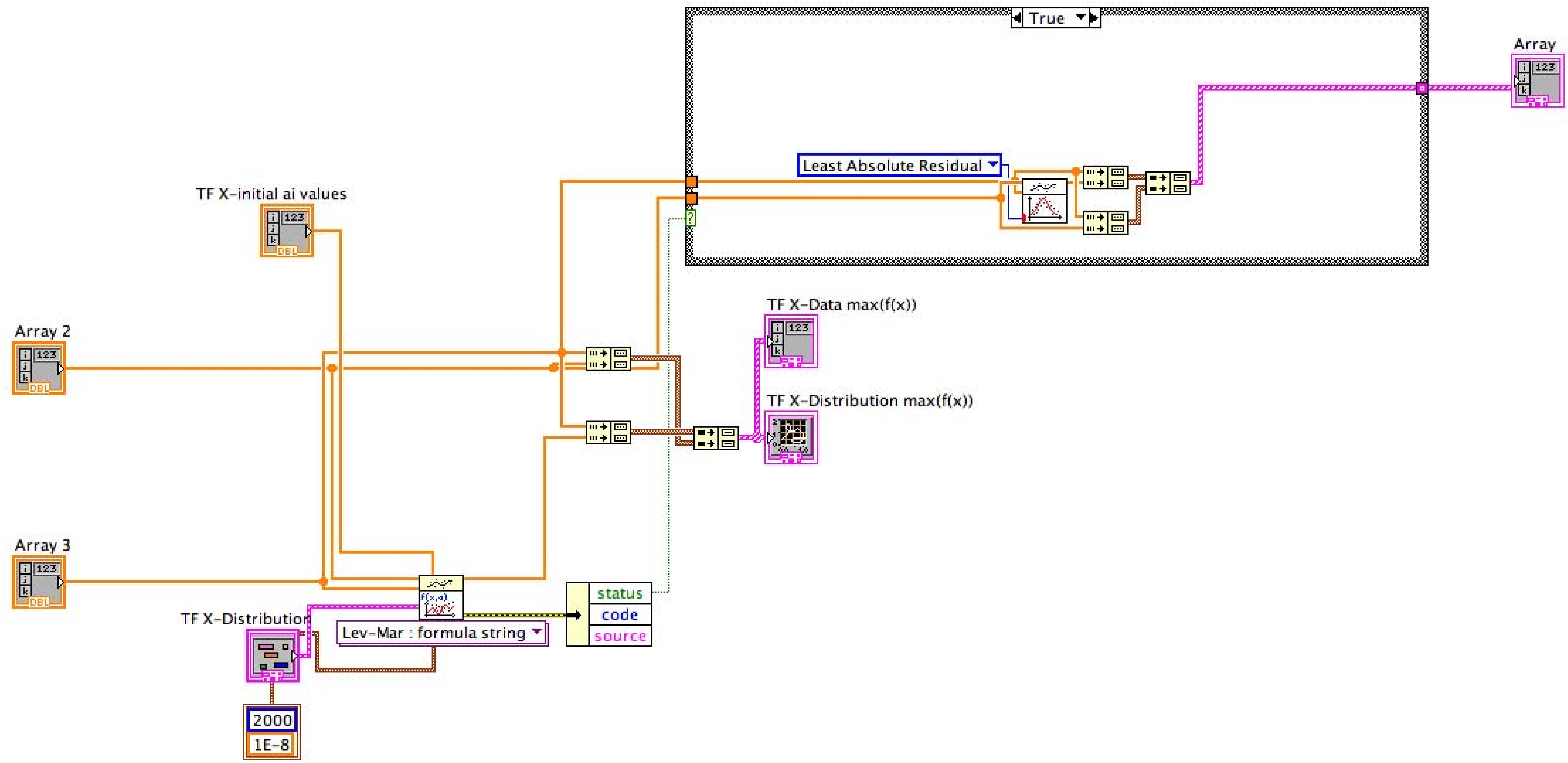
Ming-Shien Chang

$$\widetilde{n}_{\mathrm{tof,th}}(\vec{r}) = A\,\mathrm{e}^{-\frac{r_1^2+r_2^2}{2\sigma^2}},\ T \gg T_c$$

$$\widetilde{n}_{\mathrm{tof,tot}}(\vec{r}) = A\,g_2(z\,\mathrm{e}^{-\frac{r_1^2+r_2^2}{2\sigma^2}}),\ T \gtrsim T_c$$

Riemann Zeta function $g_l(z) \equiv \sum_{j=1}^{\infty} \frac{z^j}{j^l}$

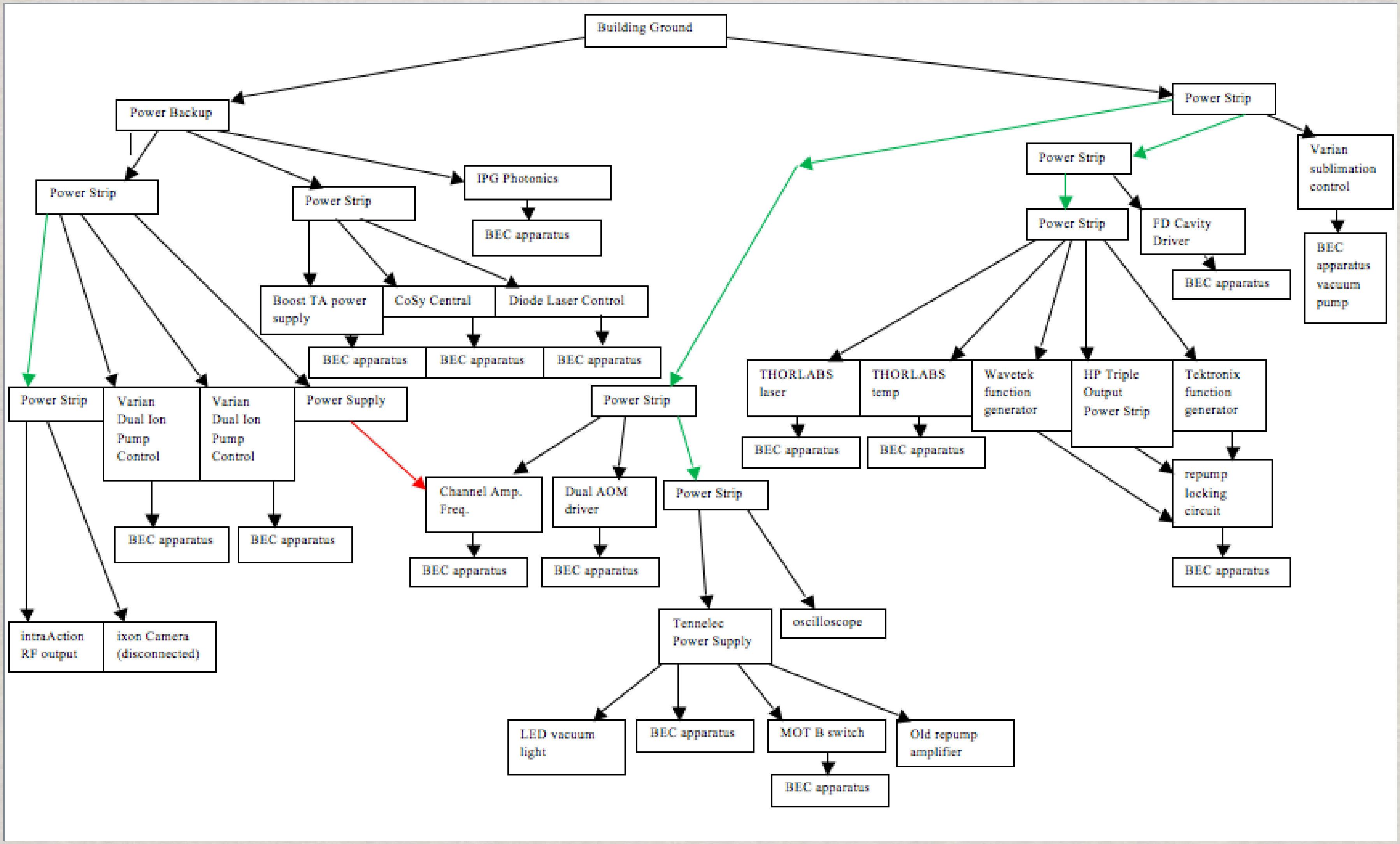
LabView Code



Project 6

- Mapped out a grounding scheme for the electrical equipment in the lab
- Hopefully after locating all the grounding sources it will help clear up grounding noise which could be preventing us from making a BEC

Electrical Diagram



Project 7

- Initially started as a project to prevent atom loss in the dipole trap
- The idea is to use a magnetic field to counter-act the force of gravity (which may be causing atom loss in the dipole trap)
- Will use a coil of wire to apply a B-field to the dipole trap which will apply a force on the atoms which is proportional to the gradient of the B-field

Magnetic Coils

- Through calculations it has been determined that the mechanism for atom loss in the dipole trap we are experiencing is not gravity

- This project is now focused on using these magnetic fields to re-create the Stern-Gerlach experiment

Stern-Gerlach Theory

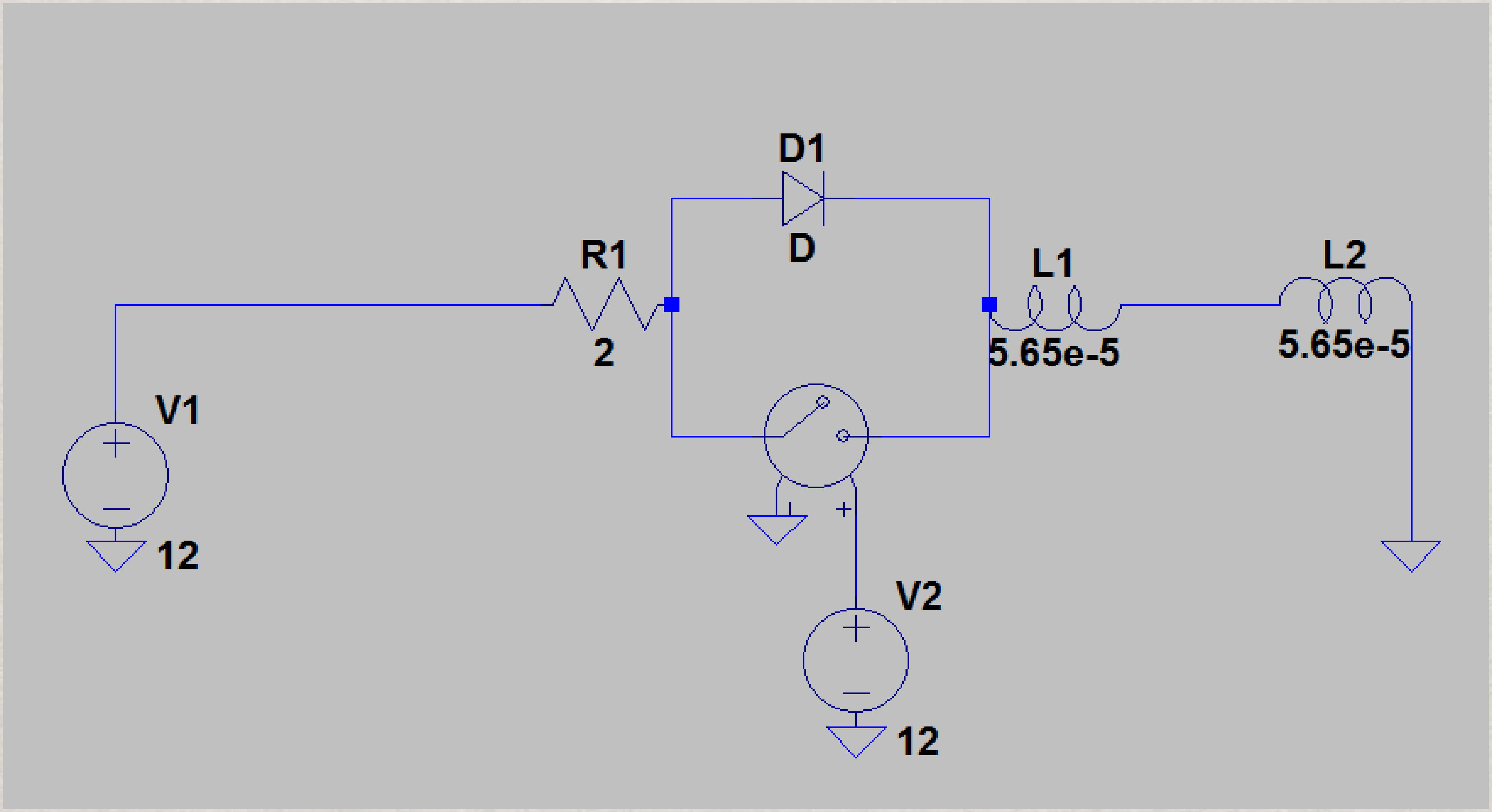
- A nonuniform magnetic field applies a force on neutral atoms and they undergo a deflection in their path

- This is caused by the spin of the atoms acting as a magnetic moment

$$\mu = -m_l g_j \mu_B \qquad U = -\mu \cdot B \qquad F = -\nabla U$$

$$|F| = \mu_B \mu_l g_j \frac{\partial B}{\partial z}$$

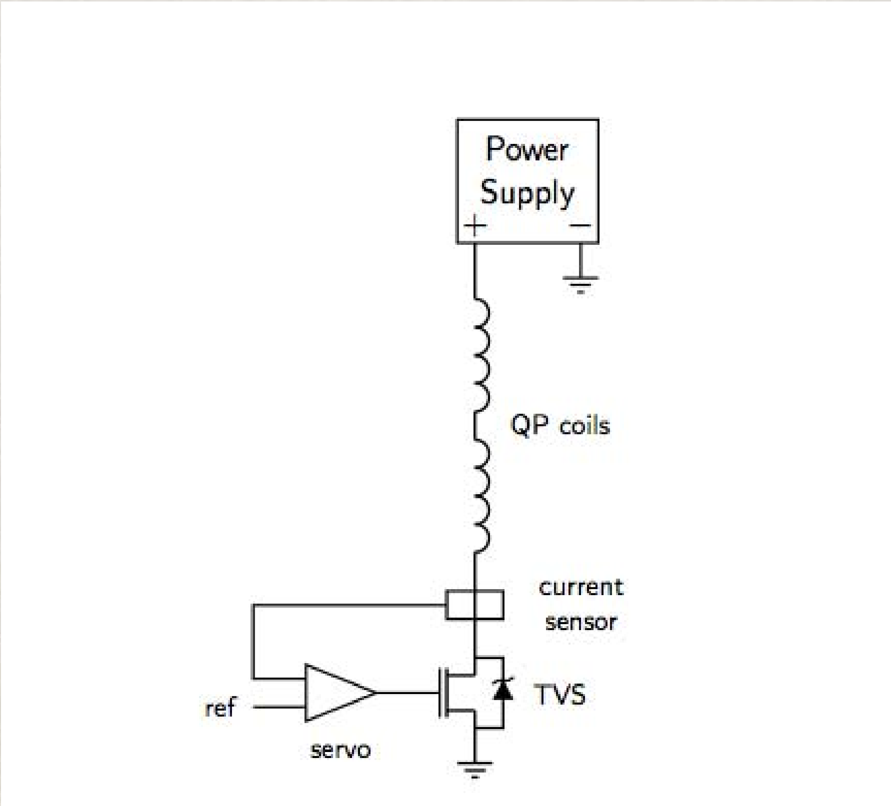
Circuit Design



Future Circuit

ULTRACOLD ATOMS IN A DISORDERED OPTICAL LATTICE

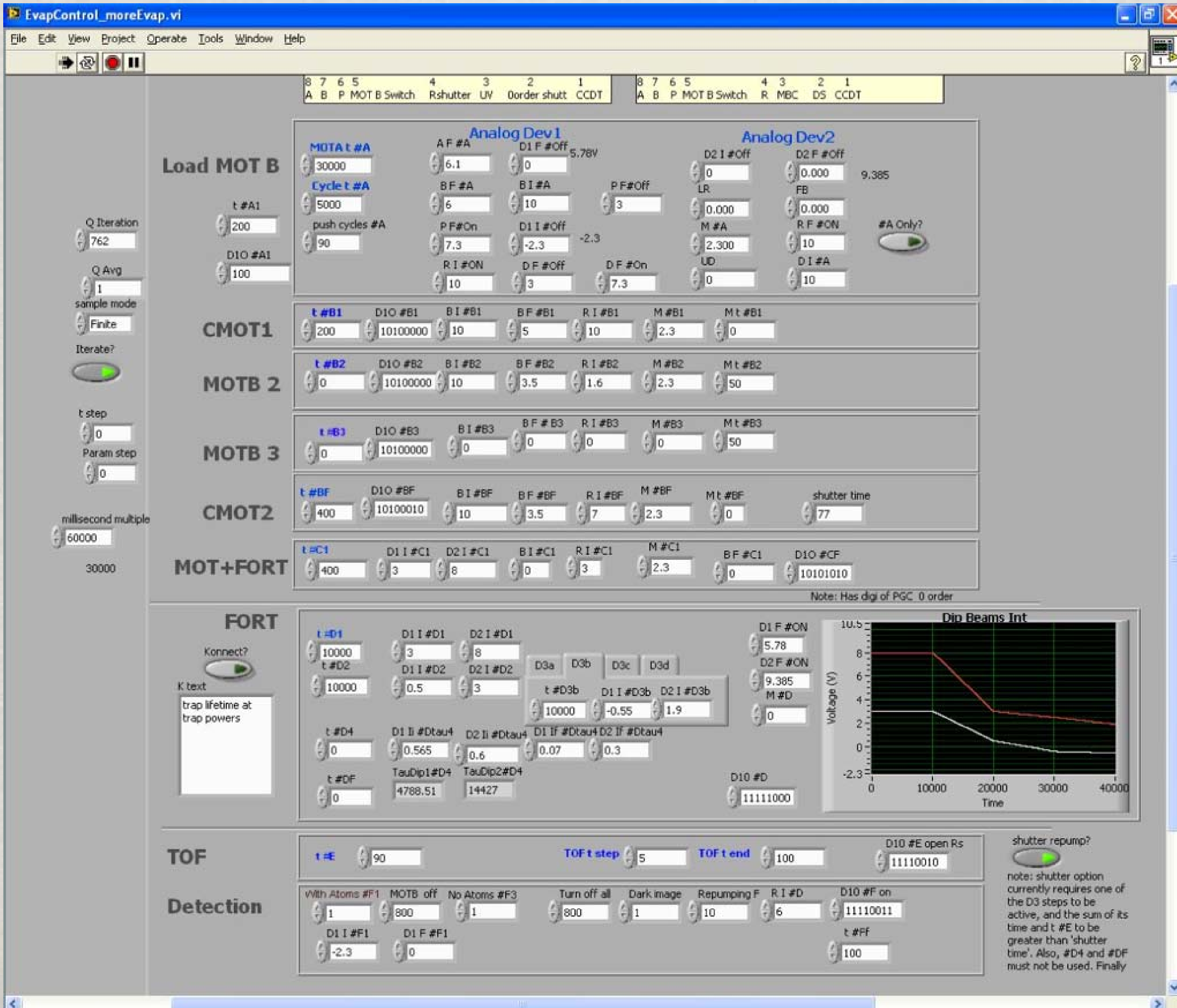
MATTHEW ROBERT WHITE



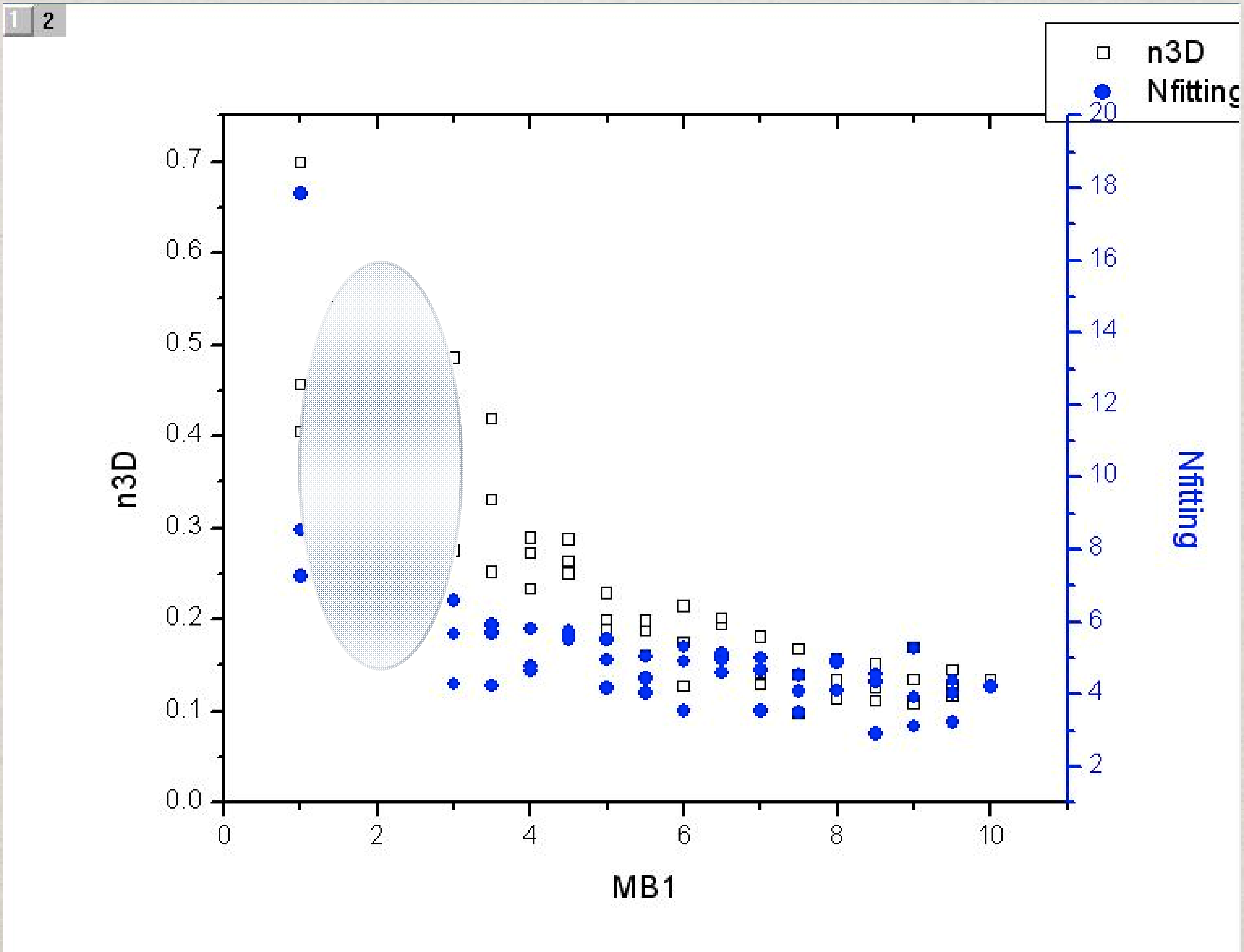
Project 8

- Working on optimizing several parameters of the MOT stage on the BEC apparatus
- Specifically changing re-pump intensity magnetic field intensity, ramp of magnetic field intensity

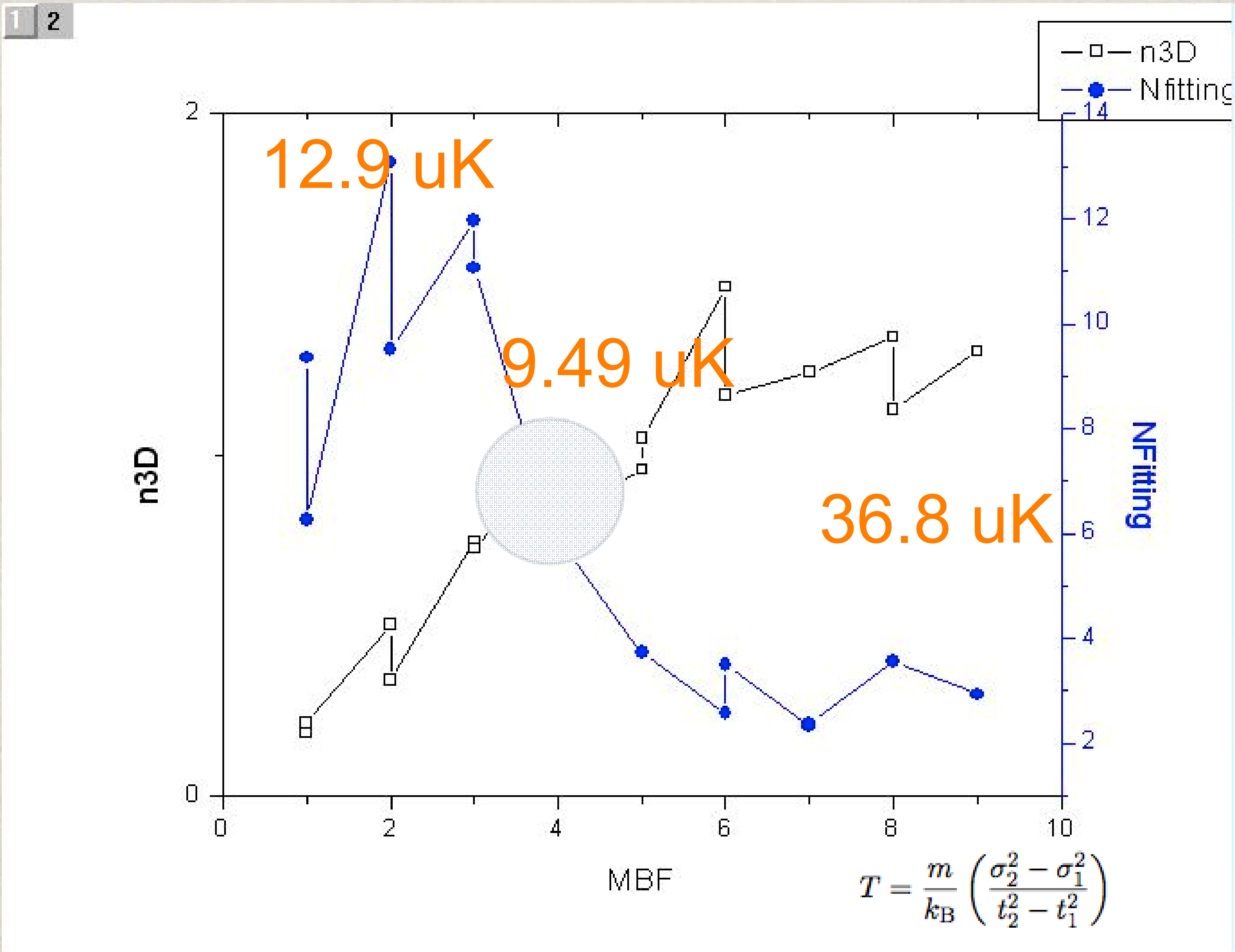
Apparatus Control



Graphs of Data



Graphs of Data



PSD ~ N/T^3