# MRI Lab 1 6.S03 – Spring 2015

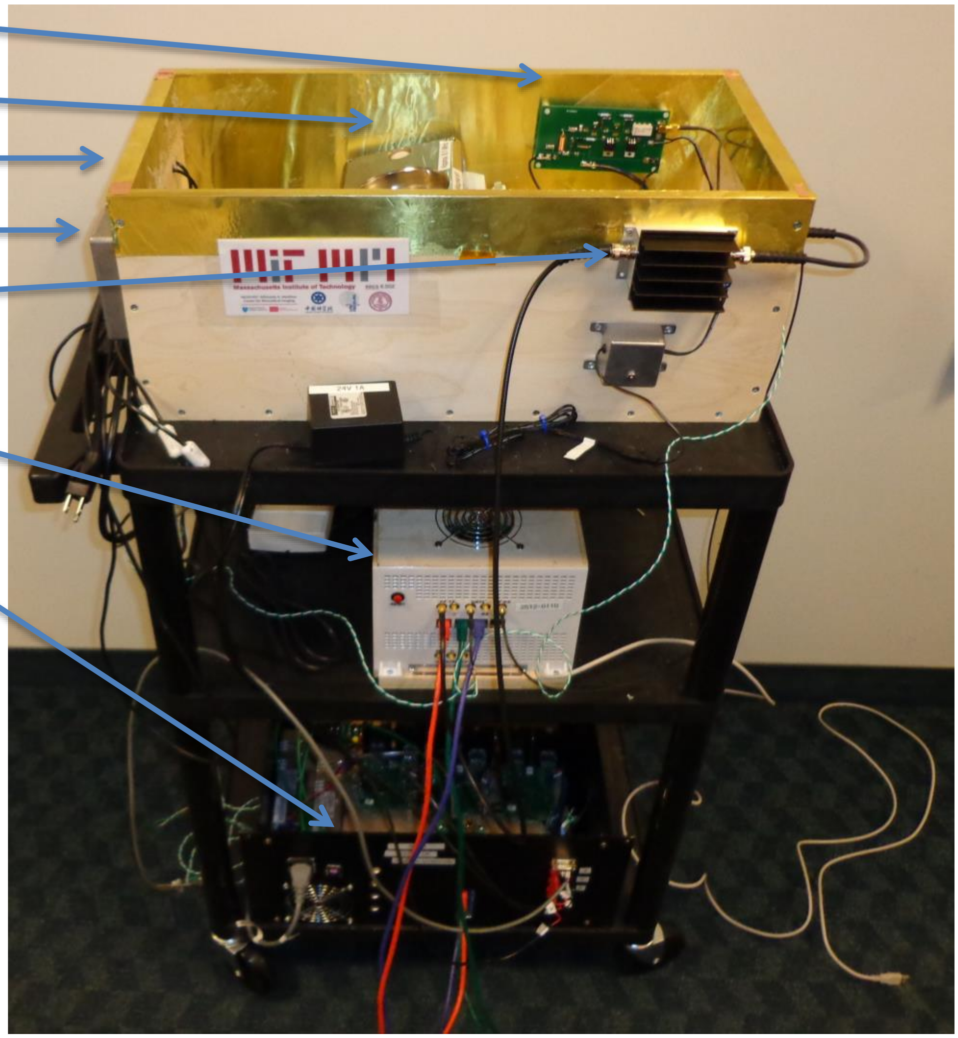
# *Free induction decay*

## 1. Getting Started

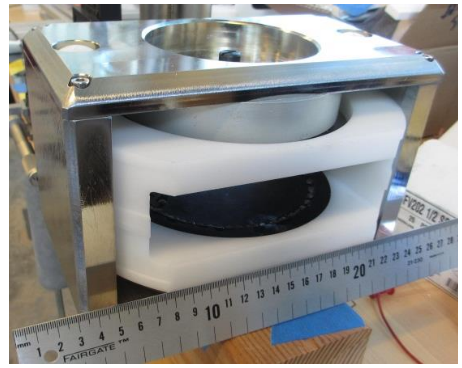
### 2.1 About your Table-Top MRI…

The system you are about to use came together across 3 continents and was the work of at least 20 people. It was coordinated by and assembled at the Massachusetts General Hospital (MGH), Martinos Center MR Physics group, with key components coming from other MR groups around the world. The rare-earth magnet was designed and constructed by the group of Prof. Wenhui Yang at the Institute of Electrical Engineering of the Chinese Academy of Sciences in Beijing. The scanner's Medusa console has been a >5 year development project by Greig Scott and Pascal Stang at the Stanford EE Department (http://mrsrl.stanford.edu/~medusa/hardware/). The gradient coil current contours were calculated by Maxim Zeitsev and Feng Jia of Freiburg University using target field design software they developed and implemented into circuit board by Cris LaPierre of MGH. The gradient amplifier was designed by Thomas Witzel at MGH. The sequence software and GUIs were written by Jason Stockmann, Bo Zhu and Clarissa Zimmerman. The systems were constructed and tested by Clarissa Zimmerman, Jason Stockman, Lawrence Wald, Cris LaPierre and Bo Zhu at MGH.

## 2.2 System Orientation



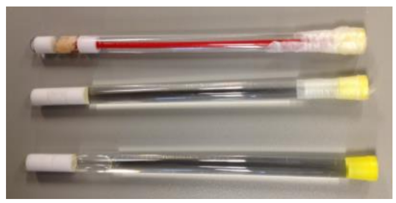
## 2.3 The System components



### 2.3.1 Magnet

The $B_0$ field is created by a small 0.19 Tesla permanent magnet. The two rare-earth magnet disks are held apart with an iron yoke, which also provides a flux-return path for the magnetic field, containing the magnetic field to the gap between the pole pieces (and inside the iron).

### 2.3.2 Phantoms

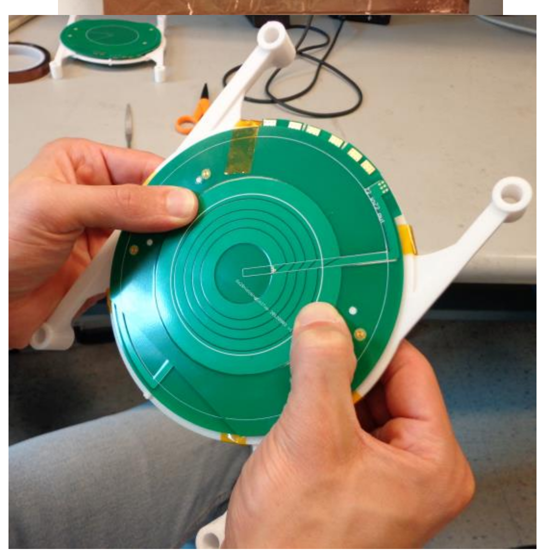


Phantoms are artificial imaging samples with known dimensions and features. For this MRI system, the imaging phantoms are contained in 1cm diameter glass tubes.

### 2.3.3 RF coil

The RF coil for this system is used for transmitting the excitation pulse to get the magnetization precessing and to detect the MRI signal through the Faraday detection principle. The coil is part of a resonant circuit that is tuned to the Larmor frequency of the $B_0$ magnet. The coil is a solenoid into which the NMR tubes fit snuggly; it is contained in a plastic case which is wrapped in copper foil to shield against external RF noise sources.

### 2.3.4 Gradient coils



The gradient coils generate the linear gradient fields that are used for imaging. They produce a magnetic field in the z direction, with amplitude that changes linearly as a function position, with a slope of 14 Gauss/cm when driven with 1 Ampere of current. With 2-A current, the slope is 28 G/cm so we refer to the sensitivity of the gradients as 14 G/(cm A). The gradient coils for this system are contained on a printed circuit board that is inserted into the magnet bore leaving a space just over 1cm for the sample and RF detector/excitation coil.

### 2.3.5 Gradient amplifier

The gradient amplifier is used to supply the current to the gradient coils. Since it's the fields we care about, and the fields are proportional to current, this amplifier can be viewed as a voltage to current transducer; it takes a voltage waveform from the console and creates a current proportional to that voltage in the gradient coil. It is similar to a common audio power amplifier except that it must also be able to output DC currents. It uses a power op-amp followed by a current sensor. The output of the current sensor is compared to the input voltage to ensure that the current itself is proportional to the input voltage. A current sensor is created by measuring the voltage across a small resistor in series with the output.

### 2.3.6 Transmit/Receive Switch

The RF coil is used for 2 things: transmitting the RF pulse and receiving the MRI signal. This means that it should sometimes be connected to the transmit amplifier and sometimes be connected to the receive amplifier. This TR switch uses passive components to effectively switch the coil connection between the two amplifiers.

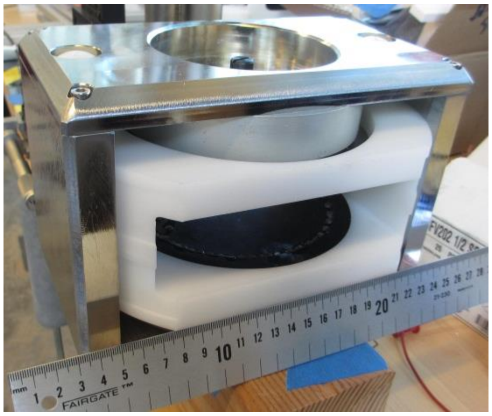

### 2.3.7 Medusa Console

The console interfaces with the computer via MATLAB. It produces the RF transmit pulses and gradient waveforms based on vectors created in a MATLAB sequence. It also acquires the received MRI signal at a time specified in the sequence. The console samples the received signal and demodulates it to baseband. Some specifics are at: http://mrsrl.stanford.edu/~medusa/hardware. The red button on this medusa console offers a hard reset of the device, which you may need to use if your experiments suddenly produce no signal and only noise. If you press the red button and wait a few seconds until you see blinking green lights, you should be ready to scan again.

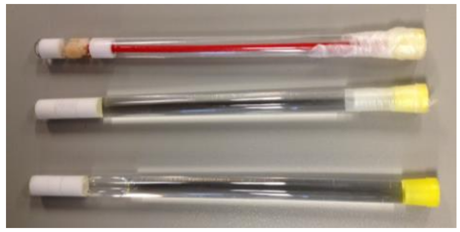
### 2.3.8 MATLAB GUI

The MATLAB GUI is what you will use to edit and run sequences. You may run an FID sequence or a spin echo sequence. You can control the amplitude of the RF pulses and gradient waveform. You will also control the repetition time (TR), echo time (TE), and the read out time.

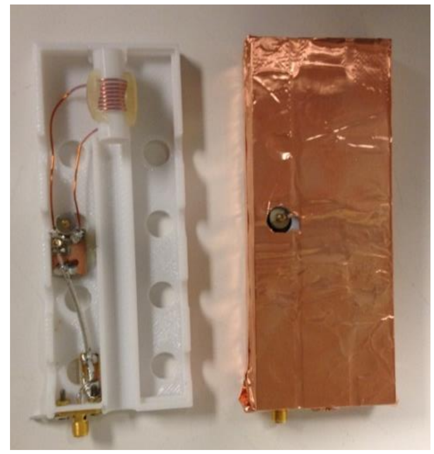
### 1.4 Summary: MRI System Components



$B_0$ Magnet



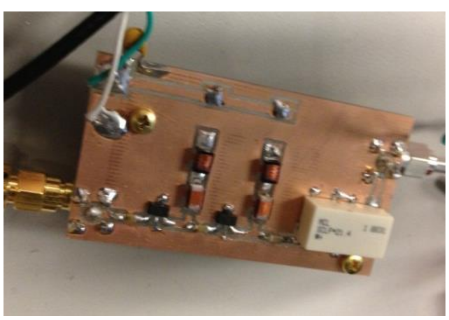

Imaging Phantoms


RF Coil and Enclosure

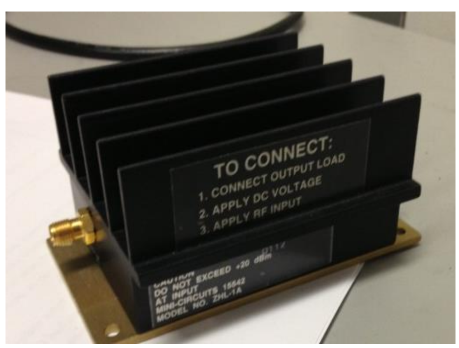

Gradient Coil PCB

Gradient Amplifiers

Console


Receive Amplifier

Transmit/Receive Switch



Transmit Amplifier

# 3. Acquire MR signals

## 3.1 Making sure your scanner is connected properly

- Plug in the power cord of your portable MRI system, turn it on, and make sure the medusa console displays a flashing green light.
- Plug in the USB cable from the portable MRI system onto your desktop station to connect the MRI hardware to your computer.
- The staff has installed the driver for the medusa system associated with your portable MRI. To launch the imaging software interface, click on the desktop icon:

- The staff already added the appropriate file paths in MATLAB. However, in case you run into directory problems, go to "Set Path" in Matlab under the Home panel, click "Add with Subfolders…" and choose C:\Users\602admin\Desktop\MRI_GUIs_v5p1 and click Save.

## 3.2 Free Induction decay (FID)

- Make sure the RF coil (wrapped in copper foil) is inserted into the magnet bore. Then insert the full water tube (phantom #1) all the way inside the RF coil.
- There is no defined stopper in the magnet for the placement of the RF coil, but you can change the positioning once you start acquiring the signals. Coil position is important and poor positioning can lead you to low signal-to-noise ratio (SNR). So if you have trouble seeing an FID signal of SNR > 200, one potential fix is to adjust the coil position. The coil position is normally stabilized with a screw. To adjust the position first loosen the screw (ask for a screw driver from the staff if you need one), then adjust the coil position until you see a high enough peak (be gentle, subtle replacement can have a big effect) and finally tighten the screw back (again be VERY gentle, you don't want to damage the coil with the screw).
- For this lab, you will use the "FID GUI". Please click on this button in the imaging software window.
- Check the "Find center frequency" box in the FID_GUI window and click "Run Scan" to let the software find the correct center frequency of the signal. The software finds the center frequency by looking at a wide range of frequencies (~250 kHz). Click "Run Scan" again to zoom into a ~30 kHz frequency range.

*Known bug:* Sometimes the frequency finder may fail to work properly. In that case please refer to the document "6.S03_2015_MRI_Lab_Frequency_and_Shim_Settings.pdf" under this lab on MITx for a good start on the center frequency and adjust it if necessary.

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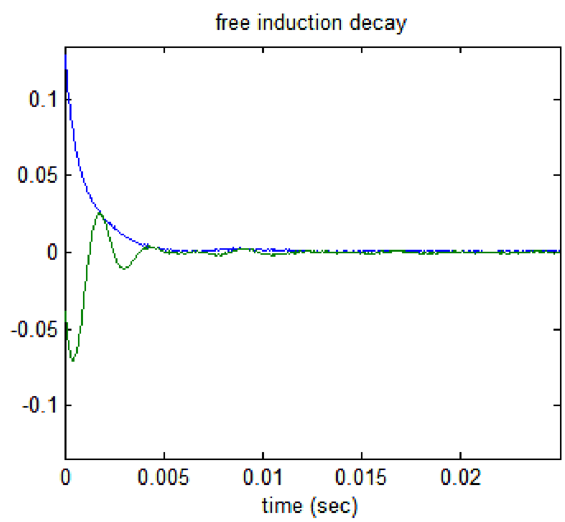
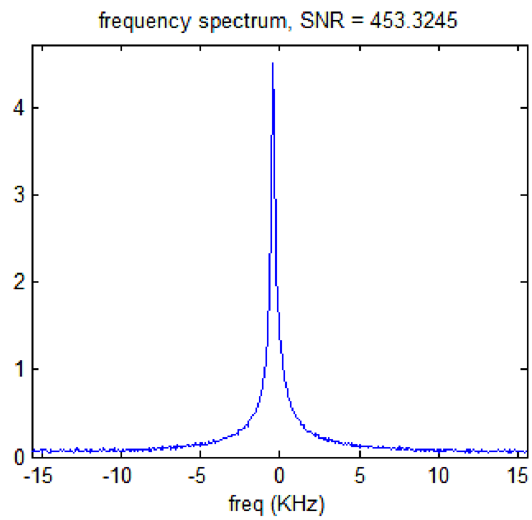
# *Free induction decay*

*Known bug:* If you don't see any signal or if the signal inexplicitly and suddenly disappears, press the "Stop Scan" button FID_GUI and press the red reset button on the Medusa console. Sometimes the Medusa console gets confused and even a reset doesn't bring it back. In this case, power cycling can help.

*Check Yourself 1.* Spend no more than 10 minutes to acquire the first free induction decay (FID), and if you are still having trouble observing an FID similar to the one below, ask for help from the staff.




- On the left is an example of a time domain signal, and the right is the corresponding frequency domain signal. This spectrum has good SNR for these systems when you use the full-water phantom (Phantom #1).
- The blue curve on the free induction decay (FID) is the magnitude of the signal and the green trace is the real component ($M_x$ component) of the signal.
- The frequency domain is displayed with the center frequency (0Hz) corresponding to the frequency value in the FID_GUI in the "Frequency (MHz)" box (for instance, 8.15 MHz).

## 3.3 Perturbing the FID with an external magnet

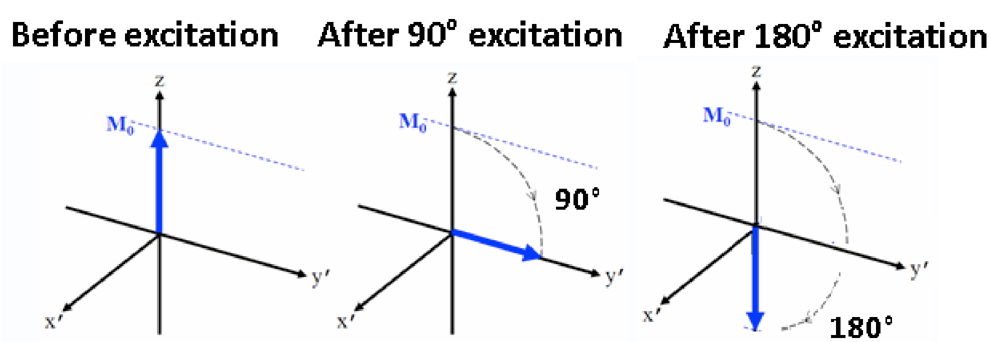
- Make sure the peak of the signal is centered at 0 Hz and if not adjust the system console frequency $f_0$ in the FID_GUI field "Frequency (MHz)" until it is. Note that the "wiggles" in the real part of FID disappear when the frequency peak is at 0Hz.

- The staff has small hand-held permanent magnets. While acquiring an FID signal, perturb the field by moving the external permanent magnet close to the $B_0$ magnet. What happens? Keeping the magnet at a position where its effect is visible, flip it around. ***Note***: The magnet is very strong! Be careful with your fingers.

*Checkoff 1 (2 points).* Demonstrate the effect of the external permanent magnet on your FID to a staff member. Describe the dominant effect of the external magnet in the frequency domain. Describe what happens when the orientation of the hand-held magnet is flipped. *Impress the staff !* by calculating the magnetic field of the hand held magnet from the change you see in your FID or its DT Fourier series.

## 3.4 Flip angle calibration

- Recall in lecture we learned about the **flip angle**, which is the angle of the net magnetization vector relative to the main field ($B_0$) direction after RF excitation. Also recall that the obtained signal is related to the component of the magnetization that is transverse to the $B_0$ field.



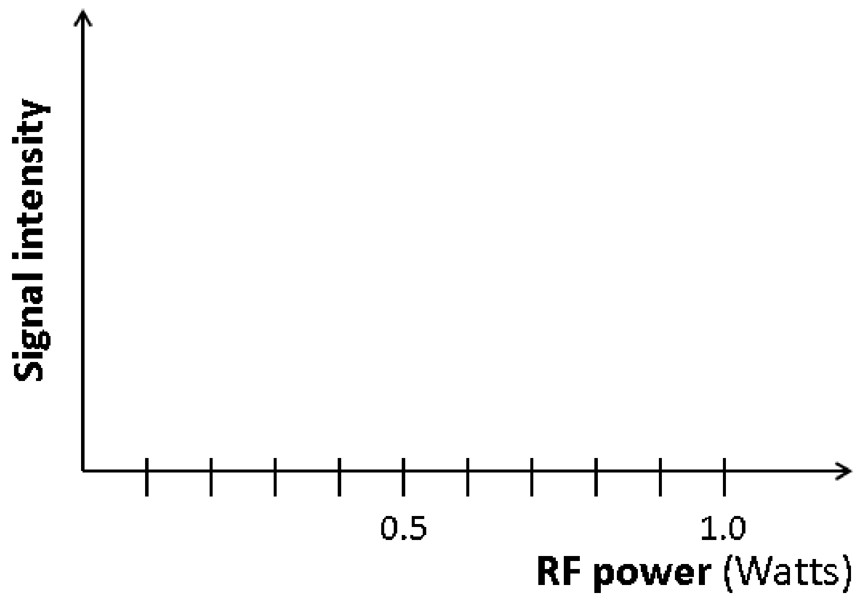

- On the excitation side, we can adjust the power of the radiofrequency (RF) pulse. This adjusts the amplitude of the RF transmit ($B_1$) pulse. Because achieved flip angle is proportional to the area under the RF pulse curve, changing the transmit power will adjust the flip angle. In this part, we will find the RF transmit powers that corresponds to 90° and 180° flip angles.

- Stop any ongoing runs, checking the “flip angle calibration” box in the FID_GUI and then start again. This automatically steps through the power of the RF excitation pulse and plots the amplitude of the FID as it goes. It steps from power of 0 Watts to ~1 Watts.
- Sketch and label the relevant features of the FID power calibration plot. Please indicate:

  a. When does the 90º flip angle occur?

  b. When does the 180º flip angle occur?

  c. Sometimes there will be a second maximum – to what flip angle does this correspond?




- Record the 90º power setting:_______________ Watts. Enter this power setting on the FID_GUI field “RF TX amplitude (0 to 1)” and use it for the rest of the lab.

## 3.5 Analyzing your FID signal in MATLAB

- Record a single FID using the RF power setting from above. Make sure to uncheck the “Flip angle calibration” box, and that the “number of repetitions” is set back to 1. Save the time domain signal (make sure to specify a filename). **Filename:____________________________**
- Write down the readout duration ___________ ms
- Load the file that you saved into MATLAB. How many (complex-valued) data points are recorded in the FID signal vector? ____________ samples

- Compute the dwell time (or sampling time for each data point) $\delta t$ = __________; and the sampling rate (also known as readout bandwidth) $1/\delta t$ =__________. Make sure to use proper units.

> *Check Yourself 2.* Your value for the sampling rate should be the same as the "readout sampling bandwidth" which is displayed on the FID_GUI.

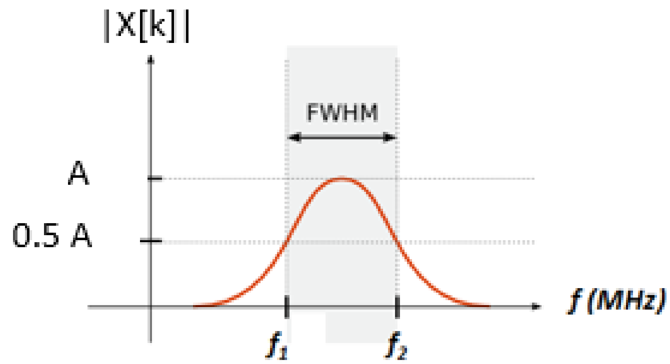
- Write a MATLAB script that:
    - Plots the magnitude of frequency domain signal of your FID, using the *fft* command you used in the previous labs. Make sure to define a frequency axis in Hz and to plot the center frequency in the center of your horizontal axis.
    - **SNR analysis:** Measure the signal to noise ratio in the **frequency domain**. Here we refer to SNR as the peak signal amplitude divided by the standard deviation of the noise. You can find the standard deviation of the noise by using the *std()* function in Matlab on the last 50 points in the spectrum. Record SNR = ____________
    - **Spectral Energy analysis:** Find the spectral energy in the frequency domain by integrating the square of the absolute value of the spectrum, so the commands *abs* and *sum* in MATLAB will help.

- **$T_2^*$ analysis:** Find the $T_2^*$ relaxation rate (ms) of the signal. $T_2^*$ is the exponential time constant of the free induction decay. In a new script, we will compute $T_2^*$ in two ways:
    - Fit an exponential function to the magnitude of the (exponential) time-domain FID. Pay attention to the units, as the *time* vector is in seconds, and $T_2^*$ is typically provided in ms. You may need to transpose your data before you use the *fit* command.

      **[curve, goodness] = fit( time, abs(readout), 'exp1');**

      If you type "curve" into the Command Window, you will see the results for the best single exponential fit to the FID data. The "goodness" structure result will help you assess if your fit is acceptable; for instance, an $R^2$ value > 0.95 indicates a good fit.
    - Measure the linewidth of the frequency domain peak. This usually is computed as the **full width half max (FWHM)**, i.e. the width of the peak at ½ the maximum peak amplitude. The $T_2^*$ relaxation rate is computed from the following equation:

$$FWHM = \frac{\sqrt{3}}{\pi\, T_2^*}$$




*Checkoff 2. (2 points)* Show your sketch of FID amplitude vs. RF pulse power. Explain the intuition behind the main features of this flip angle calibration plot. Explain to a staff member how you determined SNR and $T_2$*.

### 3.6 Magnet Shimming

- The goal of shimming is to improve the homogeneity (uniformity) of the main field, which will narrow the linewidth of the frequency domain signal. We do this by adding small, constant (i.e. DC) currents to the gradient coils. This produces a linear field variation along x, y, and z that can cancel the first-order variations in $B_0$ that exist in the magnet.
- Our goal is thus to maximize the homogeneity of the magnetic field over the sample. Since frequency is proportional to B, this means as **narrow** a linewidth as possible.
- *Hint*: The area of the frequency domain spectrum is determined by the amount of magnetization (number of protons magnetized) in the sample. This area is fixed because we are not changing the amount of water in the phantom. Because the area is fixed, the peak height of the frequency spectrum is inversely proportional to its line width. Thus to get a **narrow** line, **maximize** the peak height!

  Note that on the GUI, there is a check box for autoscaling the frequency spectrum, so you might turn this feature off.
- In the GUI, change the current offsets (mA) of the x, y, z gradient coils to apply linear shim fields along each direction. Refer to the document "6.S03_2015_MRI_Lab_Frequency_and_Shim_Settings.pdf" on MITx for a good start on the shim values. Try to further increase the magnitude of the frequency peak (i.e. make the line as

narrow as possible) by adjusting these values. Save your best shim settings using the “Save shim settings” button.

Record the currents (mA): X shim:____________ Y shim:__________ Z shim:___________

- Re-center the frequency if necessary. Record the new frequency:_________________ MHz
- Save your best-shimmed signal, and don’t forget to specify a filename.
  Filename:___________________
- Repeat *“$T_2$* Analysis”*, *“SNR Analysis*” and *“Spectral Energy Analysis”* on this new FID signal collected after shimming. Explain what has changed and why.

> *Checkoff 3. (2 points)* Show the staff member your FID signal and frequency signal with the shims zeroed (i.e. before shimming) and after the shims have been optimized. What has changed and why?

## 4. Filtering and Apodization

> *If you do not finish this section during the lab session, don’t worry! You will have the opportunity to submit your plots and explanation (in a few sentences) after the lab on MITx to receive full points for Checkoff #4.*

The goal of this section is to understand the effects on the signal and noise after multiplying the time domain signal by a “window” function. When x[n] is the recorded time domain signal (i.e. the FID), and X[k] is the frequency domain discrete signal, the two are related by the DTFS:

$$X[k] = \frac{1}{N} \sum_{n=0}^{n=N-1} x[n]\, e^{-j\frac{2\pi}{N}kn} \qquad x[n] = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} X[k]\, e^{j\underbrace{\overbrace{\frac{2\pi}{N}}^{\Omega_0} k}_{\Omega} n}$$

In this case, n is the integer index for time, and x[n] is our Free Induction Decay (FID), and k is the integer index for temporal frequency and X[k] is the spectrum. One of the tyrannies of the Fourier world is that all of the data samples in x[n] contribute to all of the values in X[k].

But what if most of the FID is noise? For example, if a long readout is used, the FID signal has decayed to near zero for most of the later samples. Then surely there is something else we can do? Can't we just zero these and reduce the noise in **X[k]** without really affecting the spectral shape?

We can take such an approach, but the elegant way to do this is so-called **apodization**, a close cousin of filtering. If we multiply **x[n]** by a function, sometimes referred to as a "window", **w[n]**, to create a new time-domain signal; **x'[n] = x[n] w[n]**, then the spectrum of this new function, **X'[k]**, is also modified. The multiplication step is called "apodizing" the FID (from the Greek phrase for "removing the foot").

Our goal is to choose a benign apodization window, such that the main signal features of the spectrum are not affected but noise has been reduced.

Load your FID signal after shimming into MATLAB (which you have saved). Look at magnitude of the DTFS (sometimes referred to as a "spectrum"). Record the spectral SNR by recording the maximum of the spectrum amplitude ($S_{max}$) and noise standard deviation (SD) by taking the standard deviation of the last 50 points in the spectrum.

$S_{max}$=___________ $N_{SD}$ = ____________________ SNR = ____________________

Now we will apply three different apodization functions, or window functions:

**Boxcar window #1:** Multiply the complex FID by a real-valued "boxcar" window function that is 1 for the first 10 points and zero after that. Take the DTFS, examine its spectrum, and estimate SNR.

$S_{max}$=___________ $N_{SD}$ = ____________________ SNR = ____________________

**Boxcar window #2:** Now do the same thing but with a boxcar where the transition occurs when the FID time signal drops below 10% of its initial value. Apply the new boxcar window, take the DTFS, examine its spectrum, and estimate SNR.

$S_{max}$=___________ $N_{SD}$ = ____________________ SNR = ____________________

**Exponential window:** Now multiply the FID by an exponentially decaying function with unit amplitude (magnitude of first point), and same time constant ($T_2$*) as you measured for the acquired FID. Make sure to define the units of the time axes properly, and recall that you computed the sampling period $\delta$t in section 1.5. Plot the magnitude of the DTFS of the apodized data, examine it, and estimate SNR.

$S_{max}$=___________ $N_{SD}$ = ____________________ SNR = ____________________

*Checkoff 4. (2 points)* Explain to a staff member what the effect of apodization in the time domain has on the spectrum, and be ready to defend your choice of the best apodization function.