BENCHTOP NMR

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OUTLINE

- Basics of NMR
- NMR spectrometer design
- My current setup
- Places to improve
- Simulation & resources

Basics of NMR | NMR Spectrometer Design | Current Setup | Places to Improve | Simulation & Resources

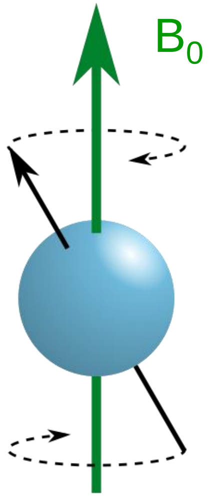
Nuclear Spin

- Fundamental property of nature that allows certain particles/nuclei to behave as small bar magnets
- When placed in a static external magnetic field (B_0), nuclei will rotate at their **Larmor frequency:**

$$f = \gamma B_0$$

  - Where γ is the gyromagnetic ratio

Nucleus	Spin (*I*)	GMR (γ) MHz/T	Rel Sens	Abund %	Comments
^{1}H	1/2	42.58	1.000	99.99	Strongest signal; occurs in nearly all biological molecules; primary nucleus of interest for MRI and MRS
^{3}He	1/2	32.43	0.442	0.0001	Like ^{129}Xe, hyperpolarized ^{3}He is used as a gaseous contrast agent for pulmonary MRI
^{13}C	1/2	10.71	0.016	1.108	Well resolved peaks, but weak signal. Requires decoupling from ^{1}H. Labeled substrates used to measure metabolism
^{19}F	1/2	40.06	0.833	100.0	Strong signal, but does not naturally occur in biologic tissues; used to label/measure drugs
^{23}Na	3/2	11.26	0.083	100.0	Strong signal, but very short T2's due to quadrupolar relaxation; no natural chemical shifts so only MRI (not MRS)
^{31}P	1/2	17.24	0.066	100.0	Strong signal, important in monitoring energy metabolism; peaks overlap
^{129}Xe	1/2	11.78	0.021	26.44	Like ^{3}He but less widely used, hyperpolarized ^{129}Xe serves as a gaseous contrast agent for pulmonary MRI



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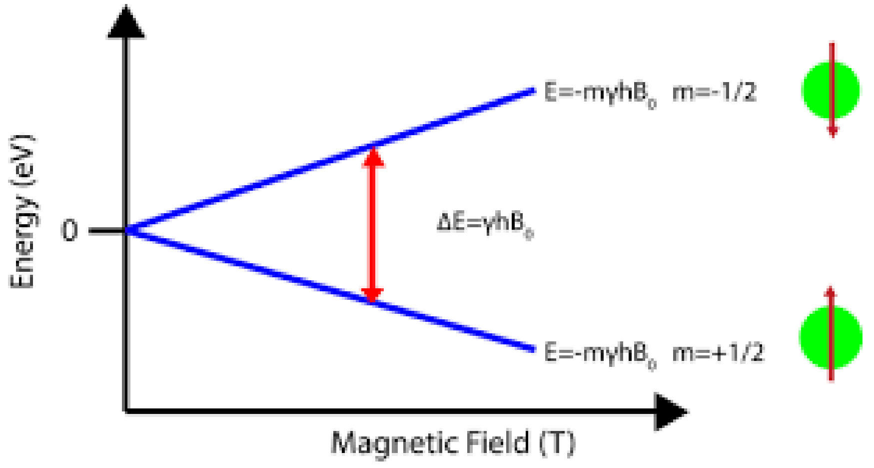
Energy & Net Magnetization

- When dealing with nuclei of spin $m_l = \pm½$ (protons) in a magnetic field B_0 , each particle will exist in one of two possible energy levels
- At room temperature, the number of spins in the lower level (N+), slightly outnumbers the number in the upper level (N-)

$$\frac{N_-}{N_+} = e^{\frac{-\Delta E}{kT}}$$

- The signal in NMR is proportional to the population difference in these states, which is why lower temperatures are used in commercial spectrometers

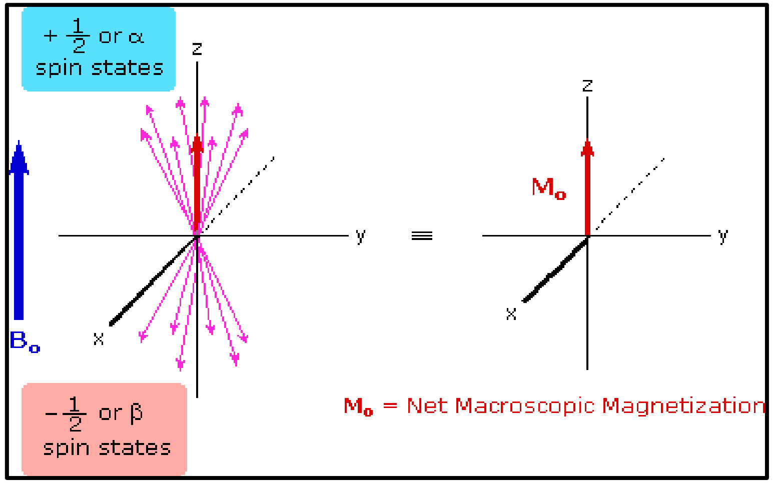


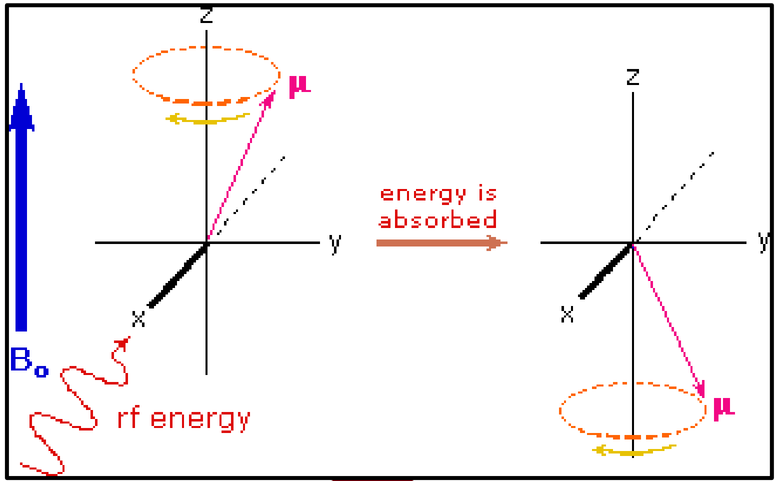
Energy & Net Magnetization

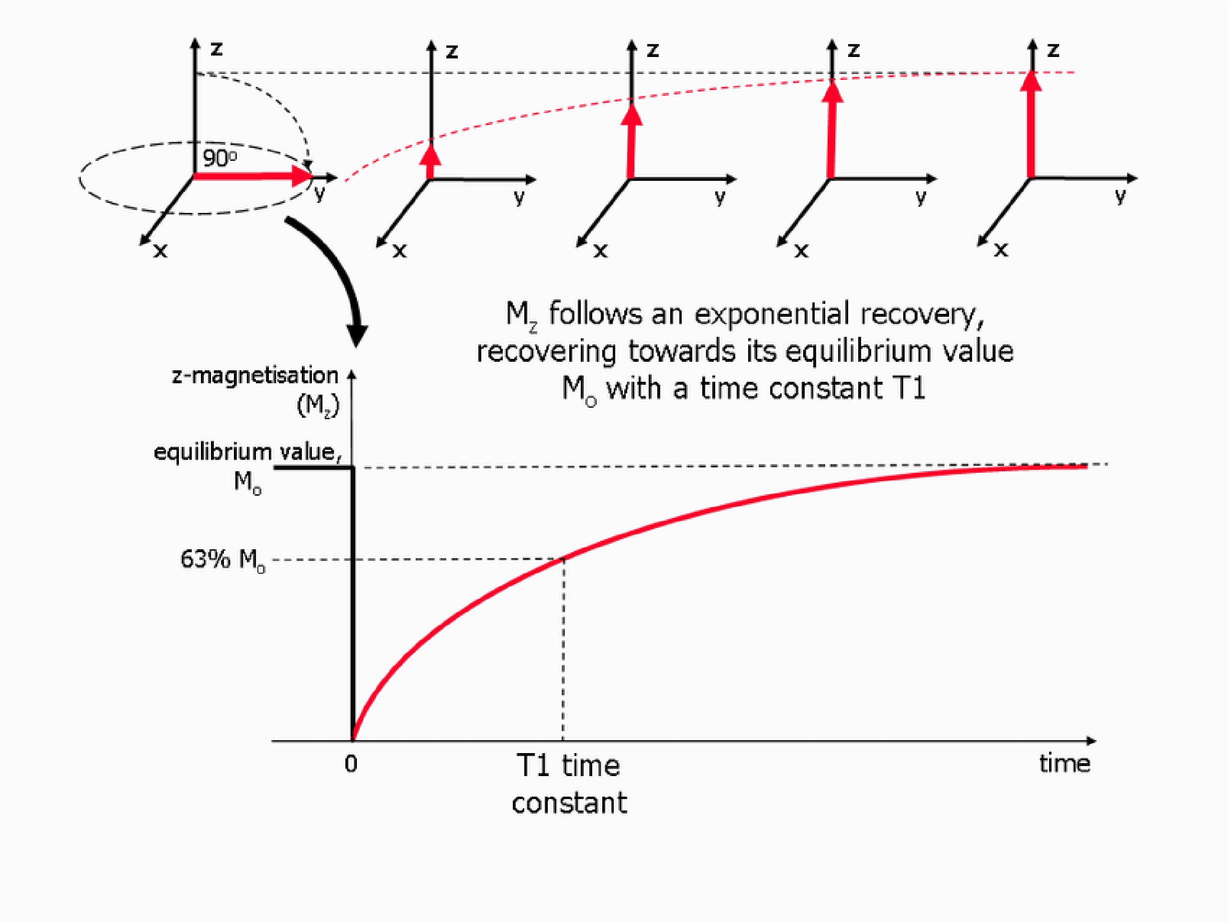
- A sample inside of a magnetic field will have a net magnetization (M_0) on the z-axis proportional to the difference in the two spin populations

$$M_0 = M_z = \sum_i \gamma \hbar m_{Ii} = \frac{1}{2}\gamma\hbar(N_+ - N_-)$$

- If an oscillating magnetic field (B_1) is applied, energy goes into the system due to this imbalance and the populations eventually become equal ($M_z = 0$)
- The moments will give energy back to their surroundings and M_z will return to its original value
- M_0 can be shifted into the x-y plane using this method







T1 Relaxation

- If enough energy is put into the system with an RF B_1 field, the system can be saturated such that $M_z = 0$
- The time constant that determines how M_z returns to equilibrium is known as **spin-lattice relaxation**, or **T1 relaxation**

$$M_z = M_0\left(1 - e^{-t/T1}\right)$$

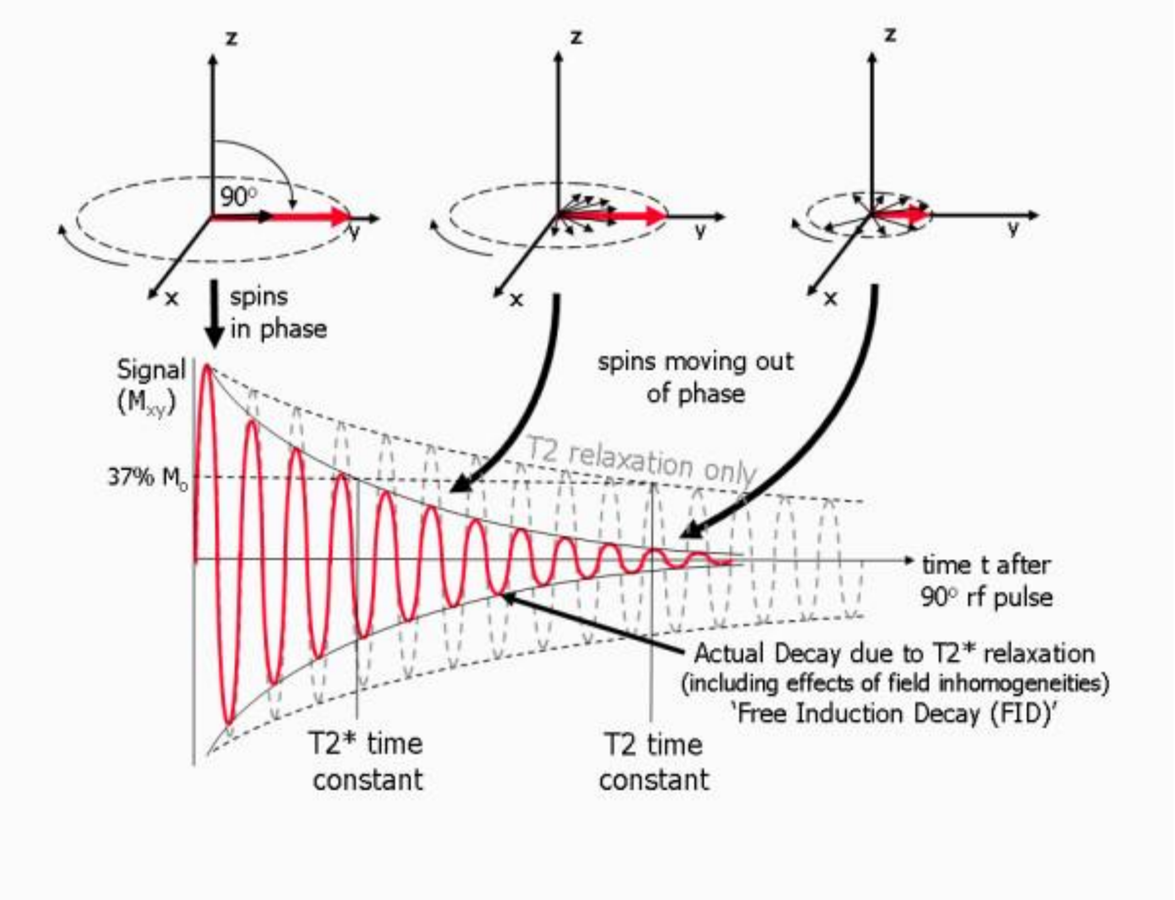
T2 Relaxation

- An oscillating B_1 field is applied that shifts M_0 into the x-y plane
- The time constant that determines how M_{xy} returns to equilibrium is known as **spin-spin relaxation**, or **T2 relaxation**

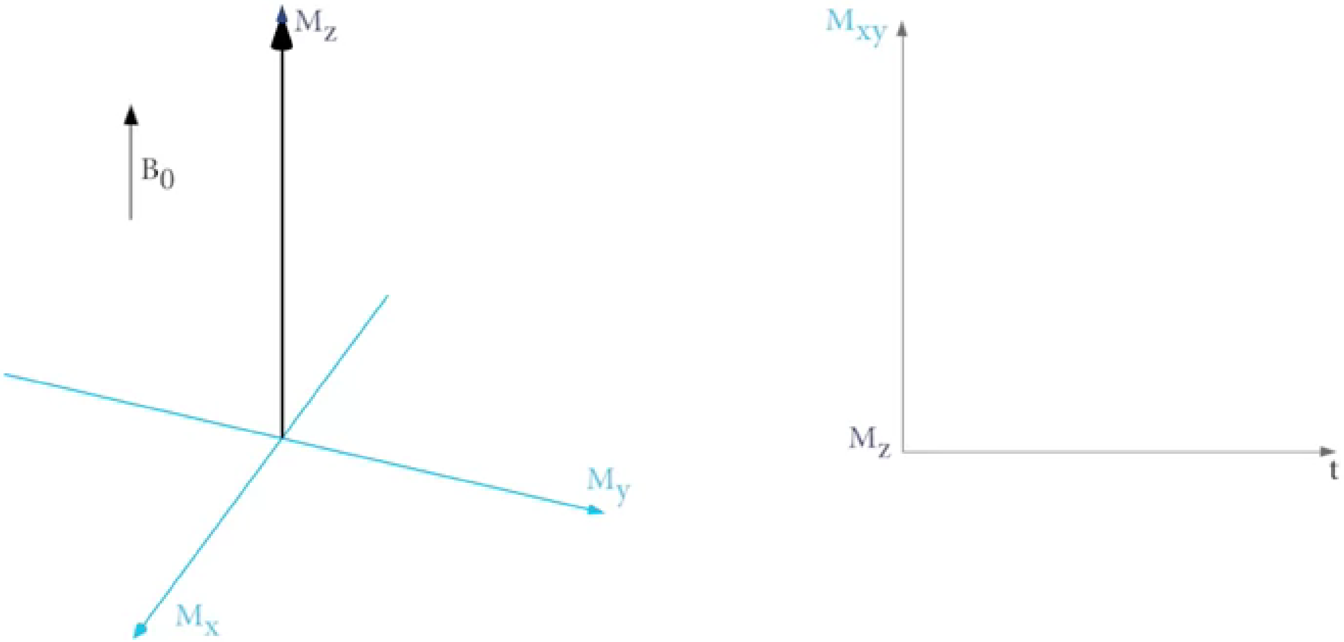
$$M_{xy} = M_{xy,0}\left(e^{-t/T2}\right)$$

- Known as **'Free Induction Decay'** (FID)
- The observed relaxation **T2*** is much less than the pure T2
  - Molecular interactions
  - Inhomogeneities in the static B field (ΔB)

$$\frac{1}{T2^*} = \frac{1}{T2} + \gamma \Delta B$$

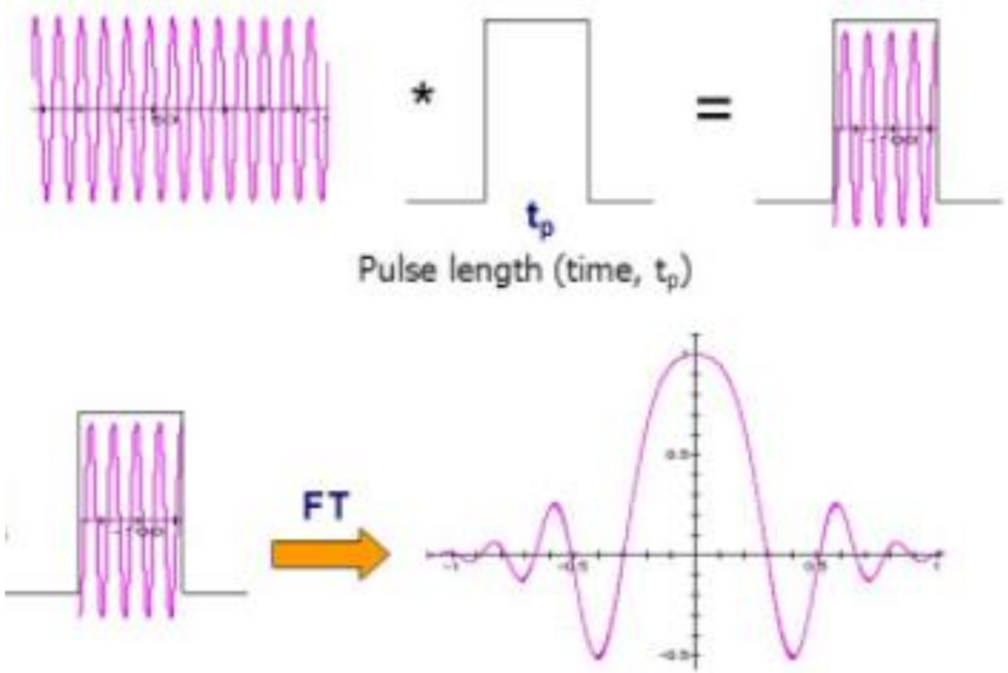


T1 and T2 Relaxation - Animation



Pulsed NMR

- RF excitation is applied in a series of short bursts that applies torque which rotates the net magnetization by a specific amount
- The duration is on the scall of **microseconds (μs)**
- Since the nuclei all have slightly different Larmor frequencies (B field inhomogeneities), the excitation frequency must cover a range
- This is achieved by the **combination of a square pulse and a cosine wave**

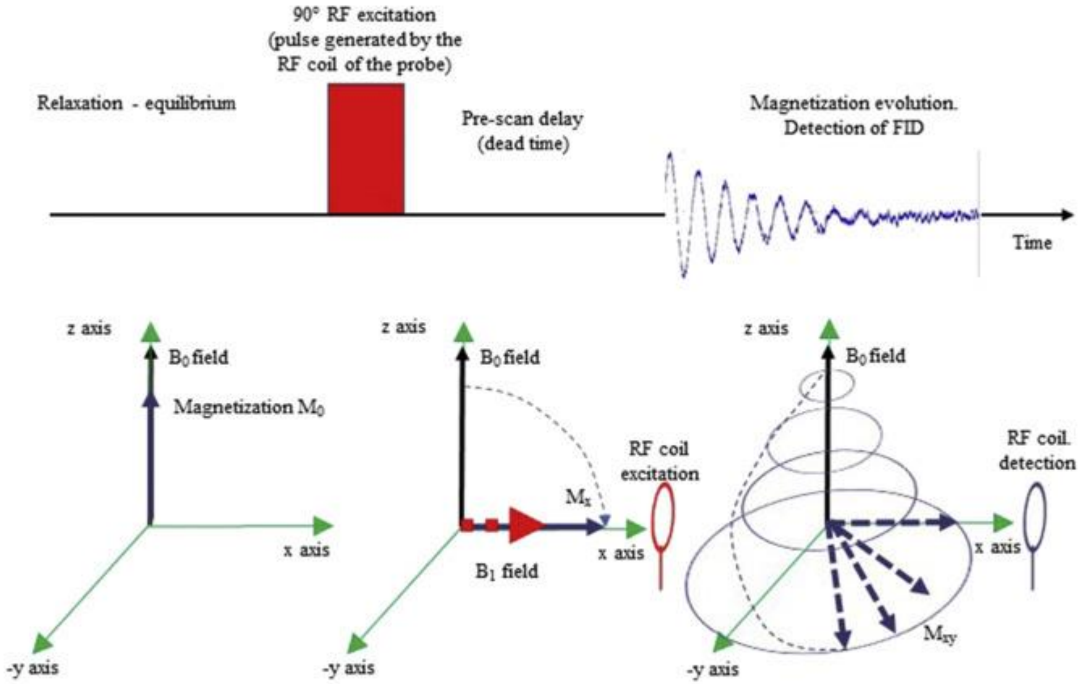


Pulsed NMR

- A **π/2 (90°) pulse** is the most common, and will rotate M_0 from the z axis into the xy plane, where it will then precess around the z-axis back to the equilibrium value

$$t_{\pi/2} = \frac{\pi}{2\gamma B_1}$$

- Pulse **sequences**, such as a 90° followed by a 180° pulse, are also very important for determining other sample characteristics
- We will focus on the 90° pulse and trying to acquire the basic FID for now



Equilibrium magnetization M_0 due to the static field B_0, aligned to z axis.

Magnetization tilted towards the x axis after a 90° RF pulse. In red, the RF frequency B_1 field produced by the coil.

Precessing of the magnetization in the xy plane and return to equilibrium. Detection of the electromotrice force induced by M_{xy}.

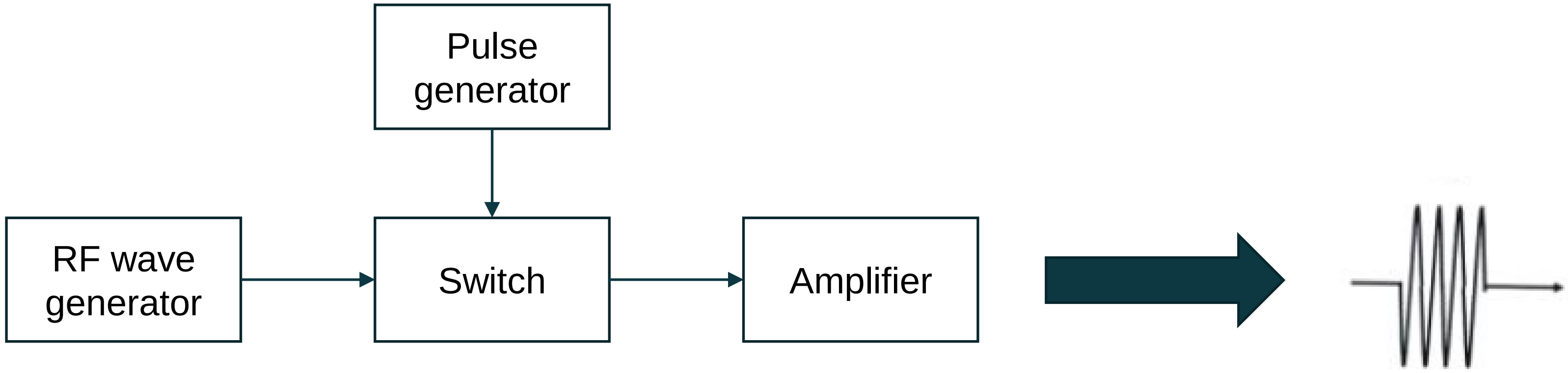
Creating & Observing T2 Relaxation

- Steps:
  1. Creation of a **net magnetization vector M_0 along the "z axis"** by placing a sample in a strong, static (and as homogenous as possible) B_0 field
  2. Application of an **oscillating transverse B_1 field at the Larmor frequency** ($\boldsymbol{f} = \boldsymbol{\gamma B_0}$) to shift M_0 into the xy plane
  3. Observe the **decay/precession of M_0 in the xy plane** as it moves back to the z axis

- Spectrometer main components
  - **Permanent magnet** - strong, static, & homogenous
  - **Transmission stage** - creation of an RF signal at Larmor frequency
  - **Probe** (inside magnet) – delivers RF B_1 pulse & collects response from sample
  - **Duplexer** – isolates the transmitter from the detection circuitry
  - **Receiver stage** – amplifies and mixes the induced signal (FID) from the probe

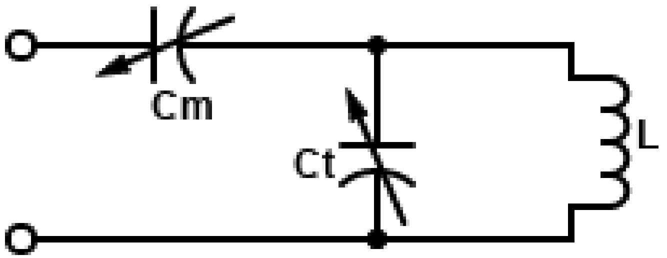
RF Pulse Amplification & Transmission

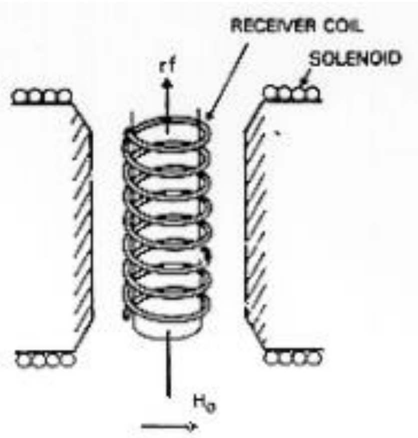
- Creating a square pulse of an RF signal at a given frequency can be achieved in many ways
- Easiest method is to use a **fast switch** as a gate to pulse the wave
- This pulse is then amplified by a large amount – enough to deliver **watts of power** during the pulse



Probe

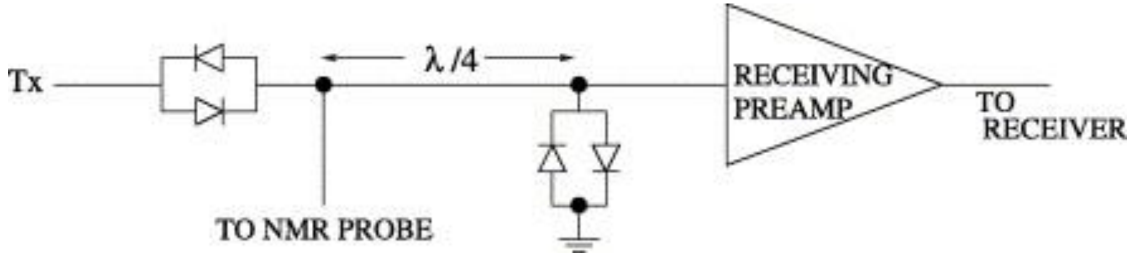
- The probe circuitry is essentially a LC tank circuit
- The capacitors Ct and Cm are used to **tune the probe to the correct frequency** and **match it to the correct impedance**
- It is crucial for the probe to be tuned and matched so that the maximum power is delivered to the probe
- The coil is placed inside the permanent magnet so that the field it generates is perpendicular to the static field

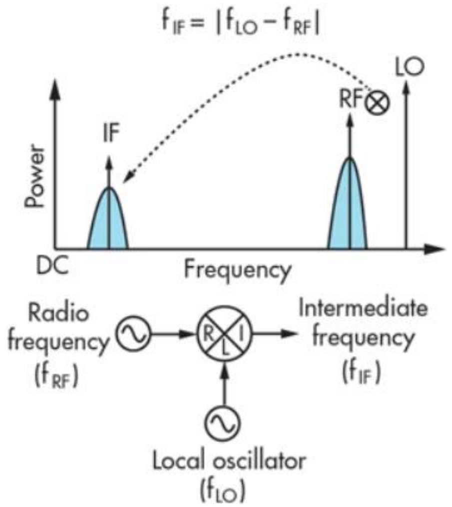


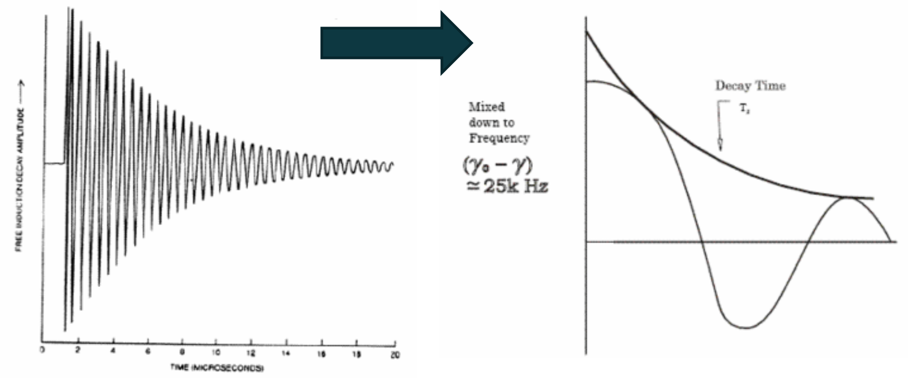


Duplexer

- This is needed since the probe is used to deliver the pulse and to pick up the resulting FID
- The transmitter and receiver must remain isolated in order to protect the amplifiers and keep the FID from acquiring extra noise
- Most common method in compact NMR is **quarter wave (λ/4) lines and diode gates**



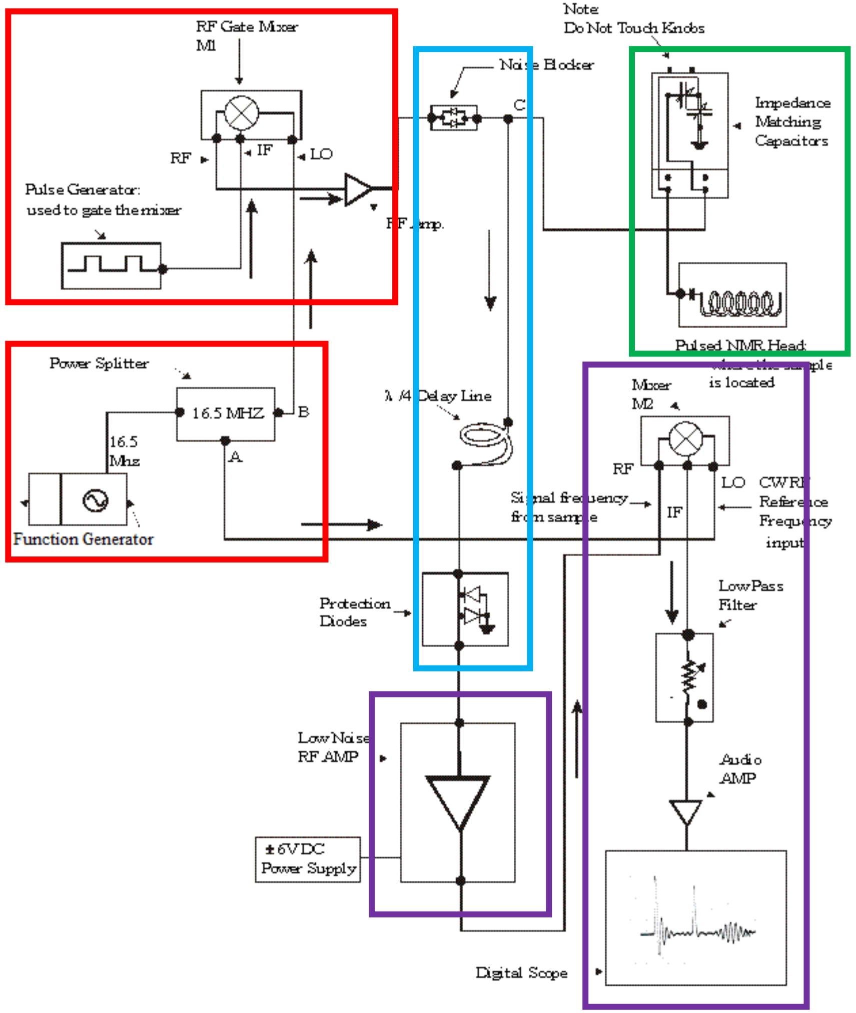


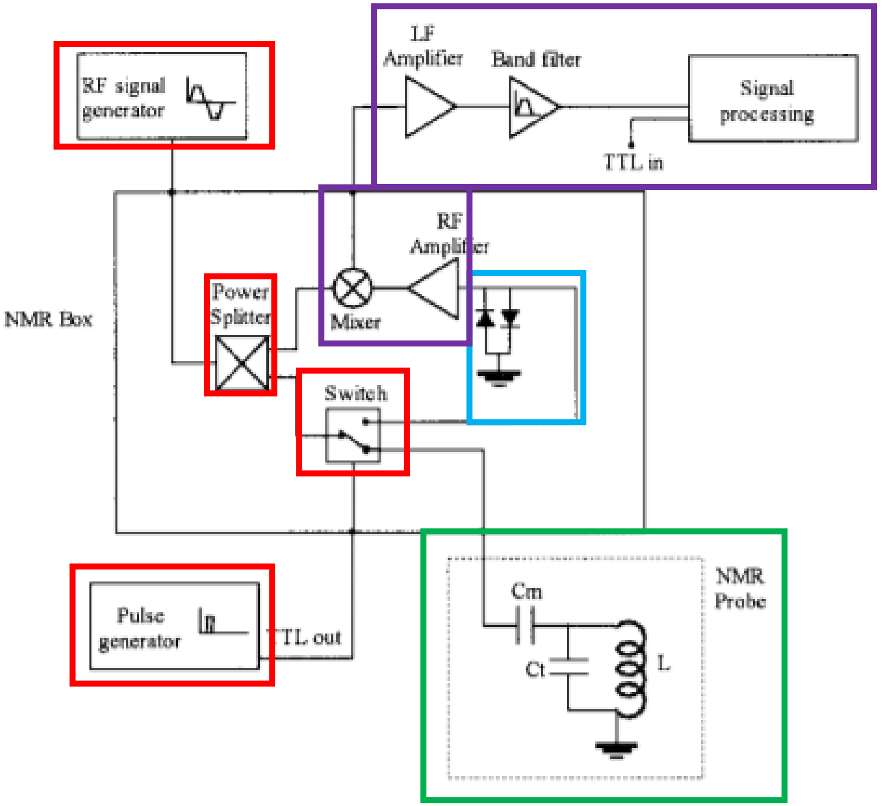


Receiver Stage – Amplification & Frequency Mixing

- The FID is in the **µV range** and must be amplified to an observable level
- Around 60 dB is typical so that it can be boosted to the mV range
- The signal then enters a frequency mixer that combines it with the same frequency used to excite the probe
- A wave with the **same envelope** (decay) but a **lower frequency** will be obtained
- This is needed to limit the detection bandwidth and make the signal easier to identify

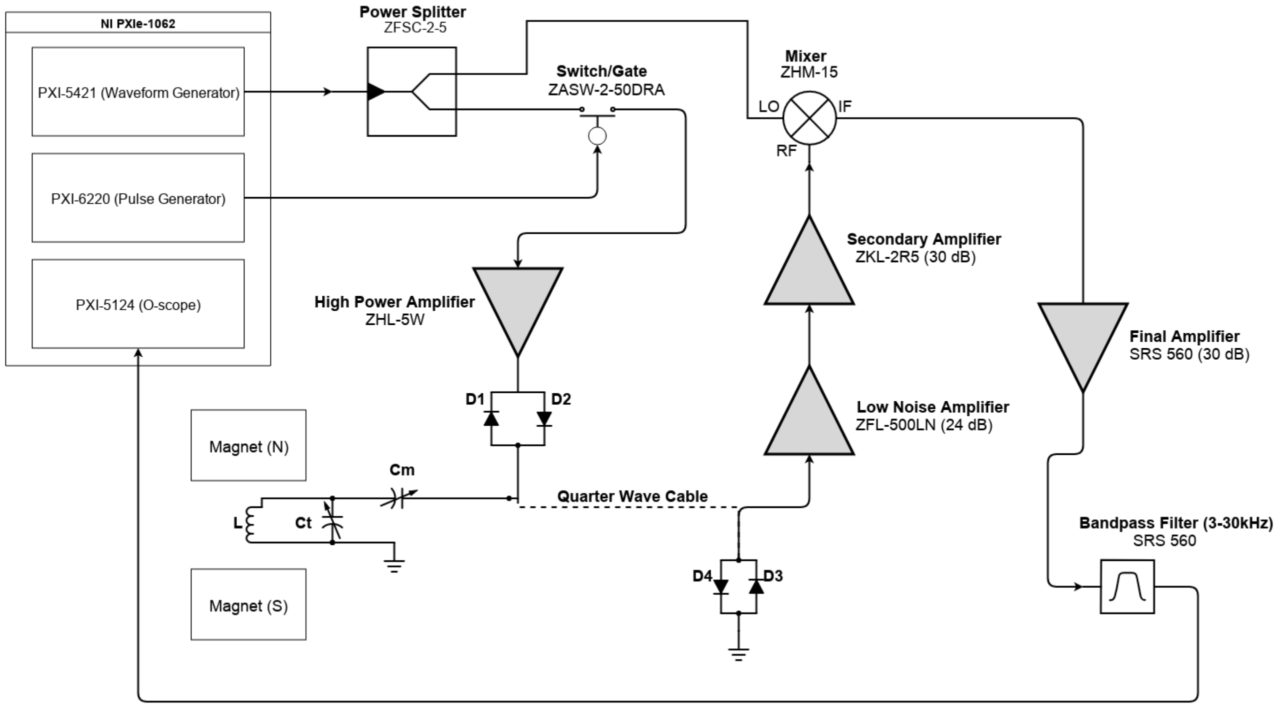
Examples of Compact NMR Designs

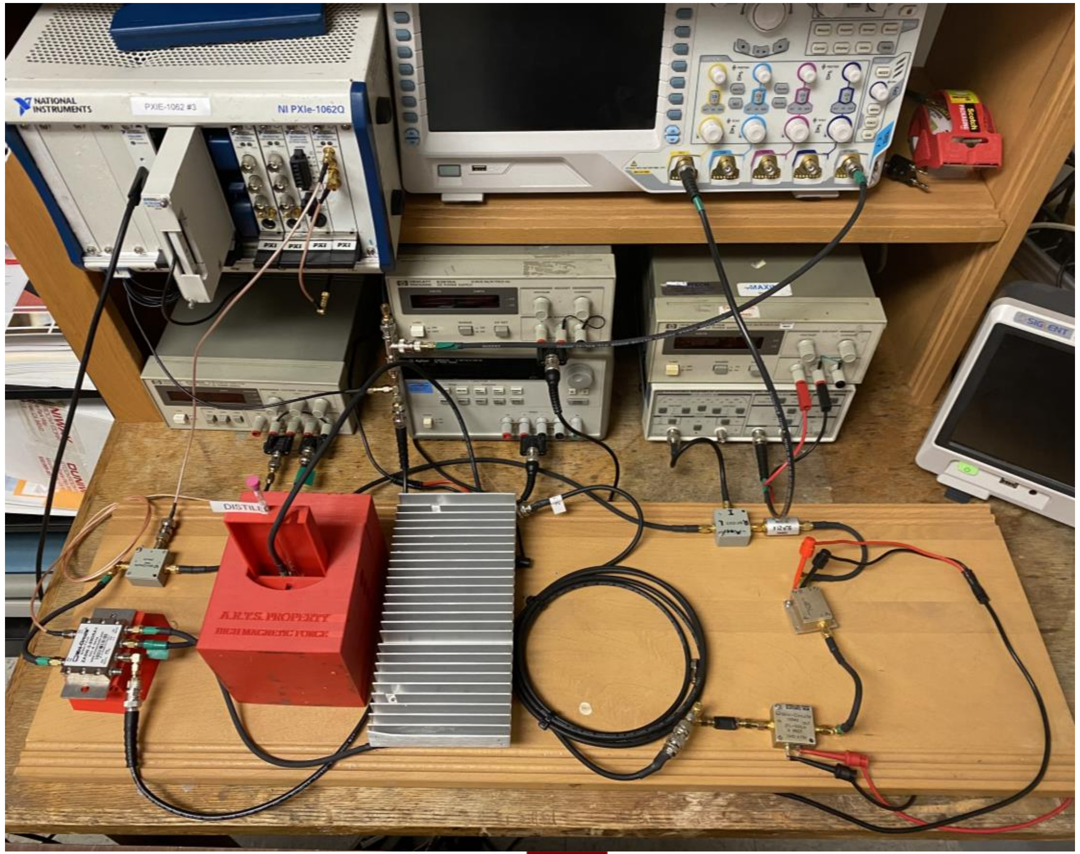




- Transmitter
- Probe
- Duplexer
- Receiver

My Setup – Full System Schematic





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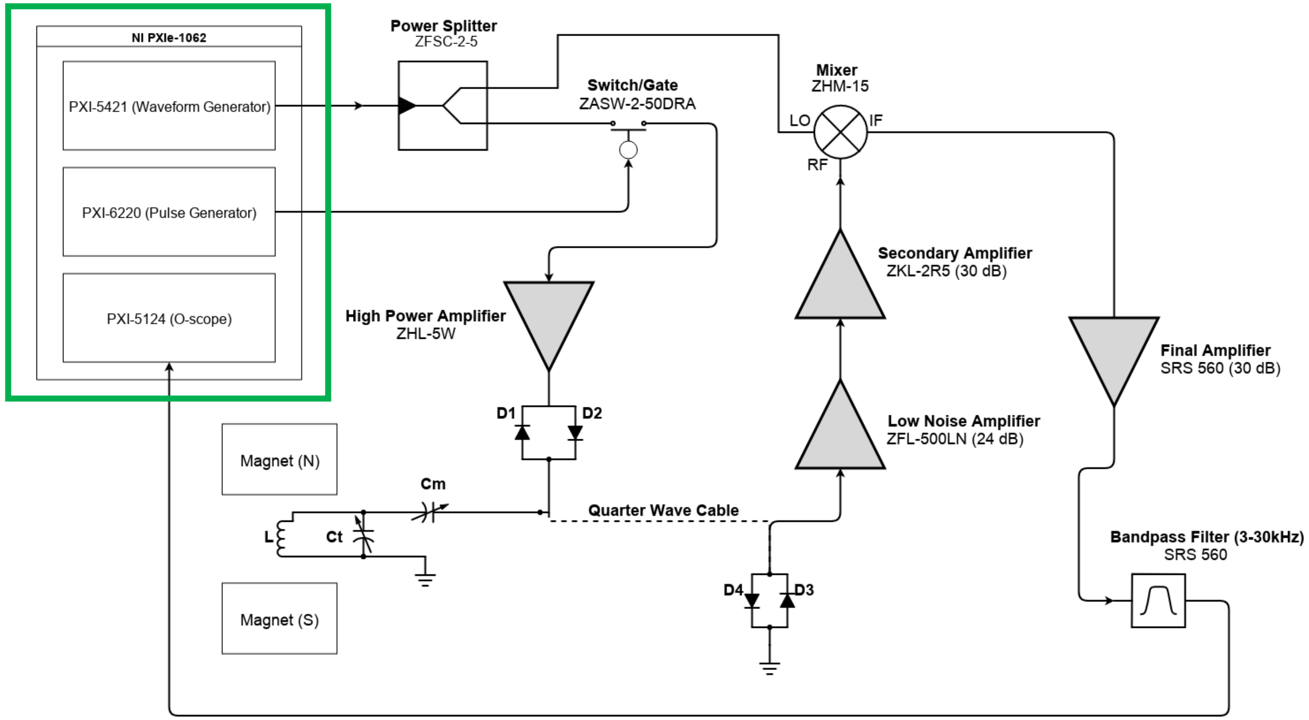

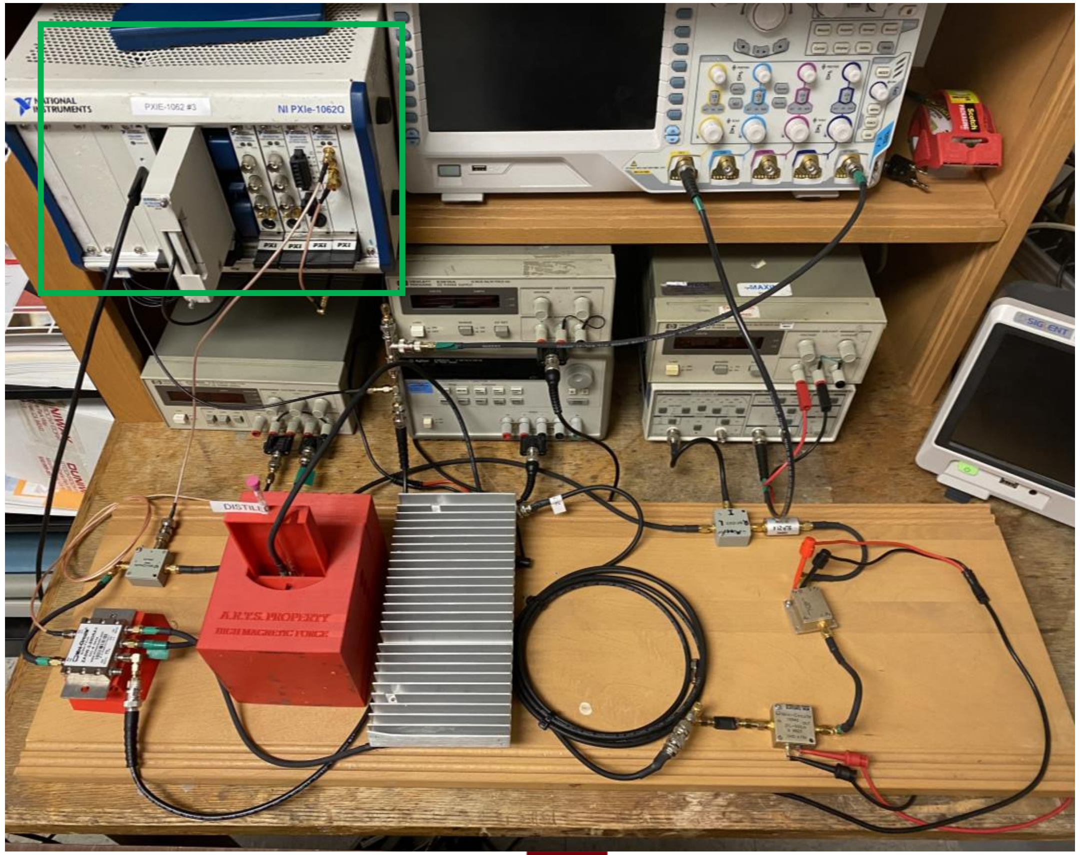

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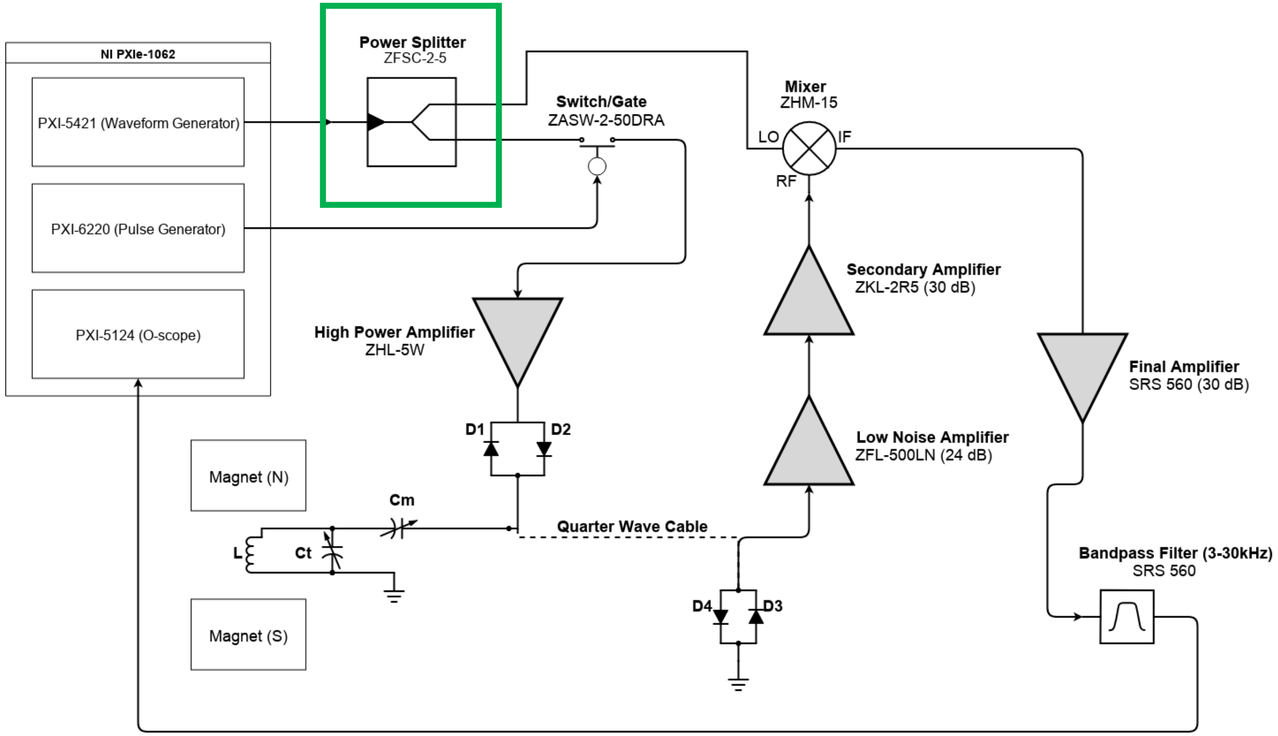

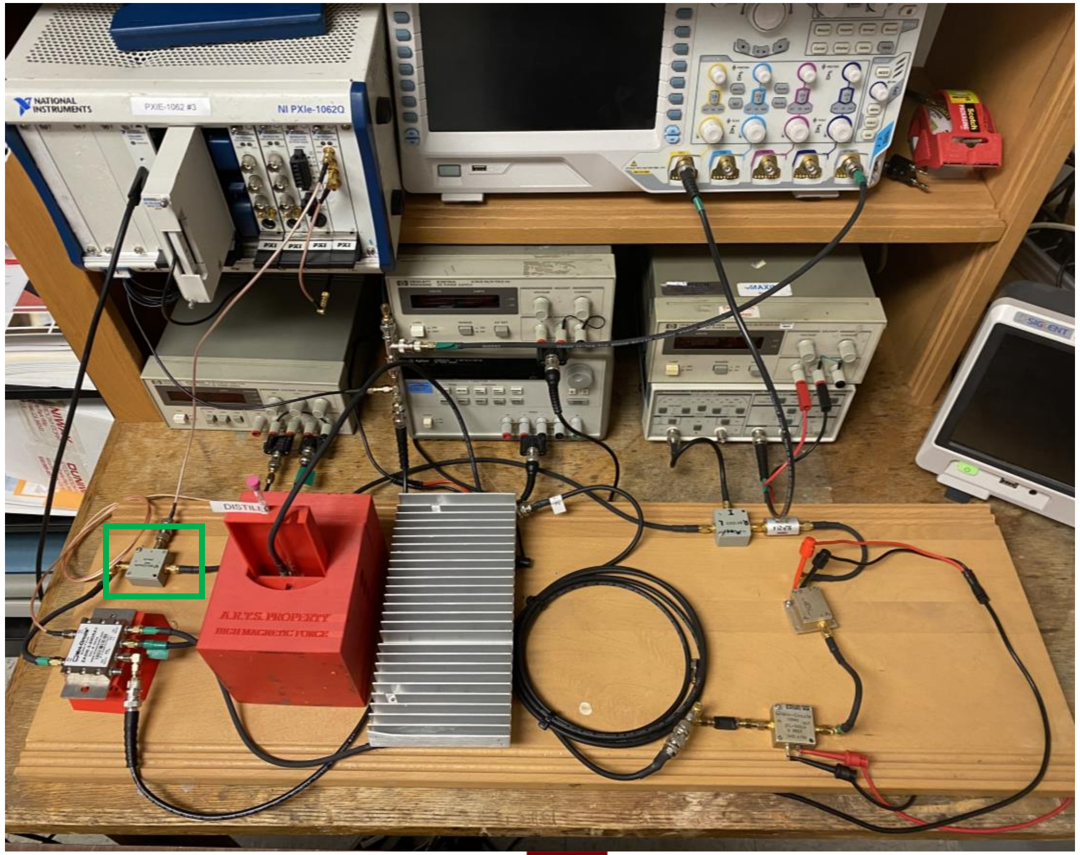

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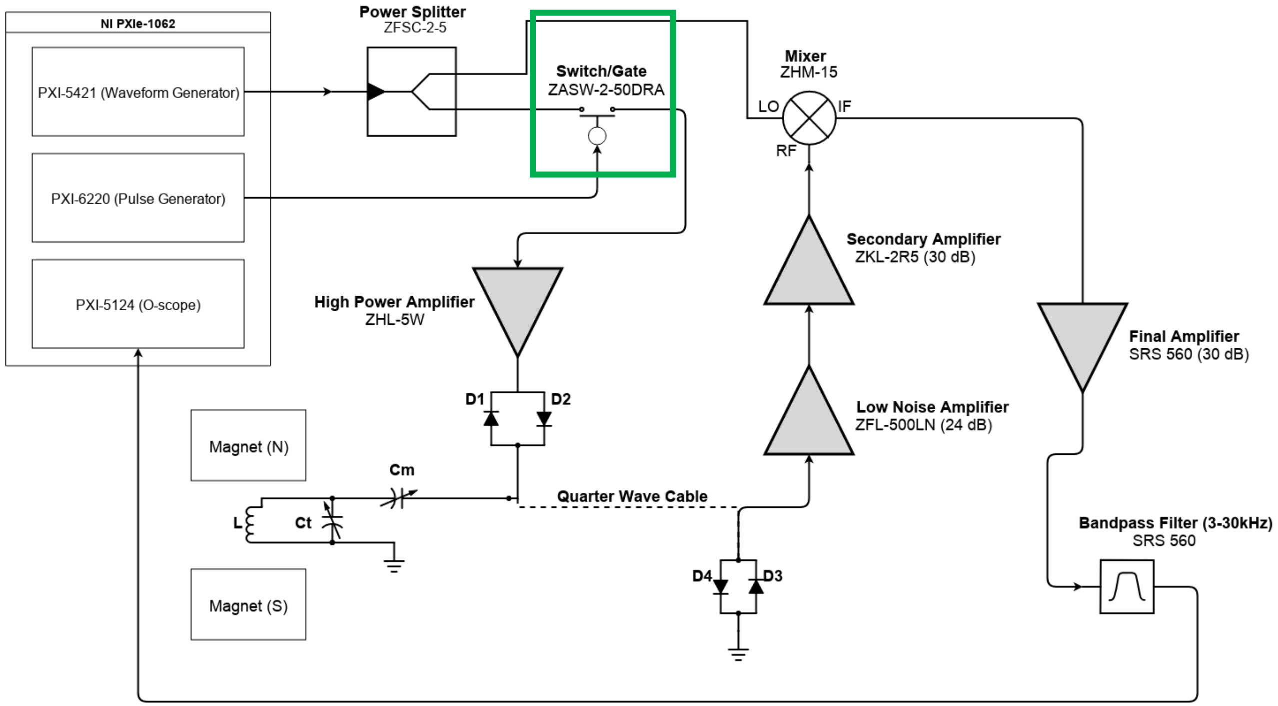

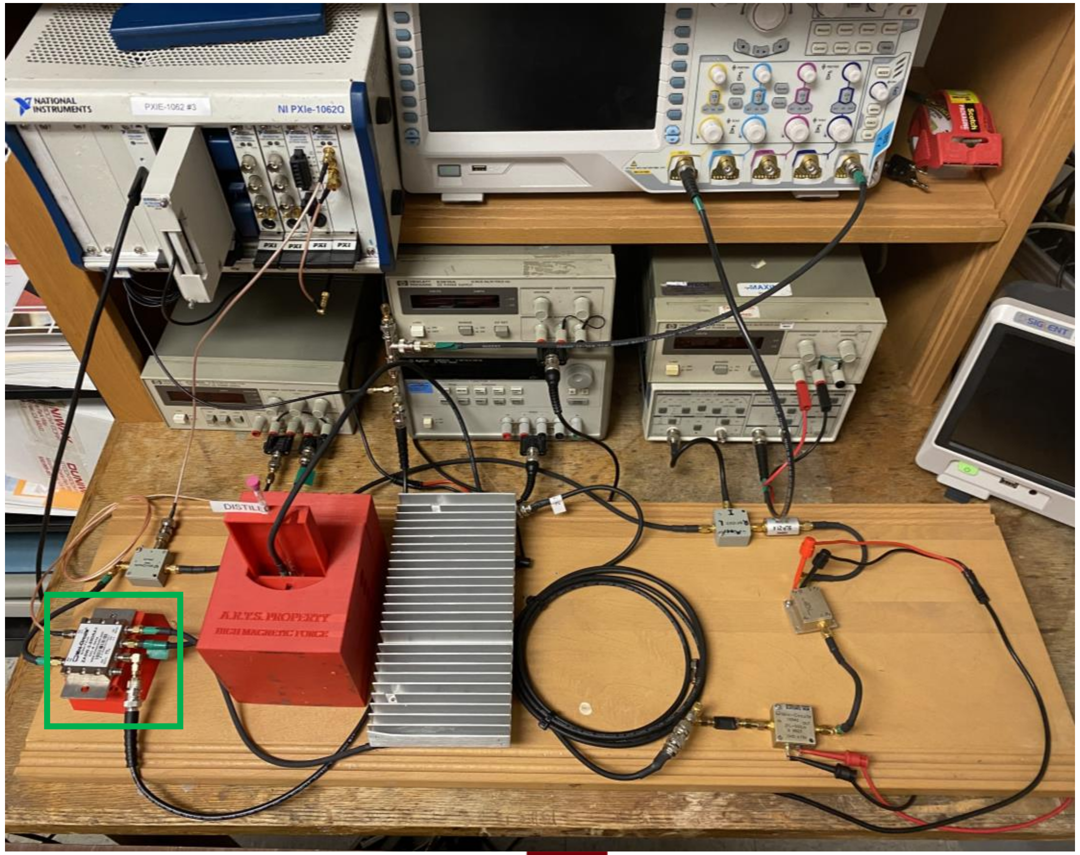

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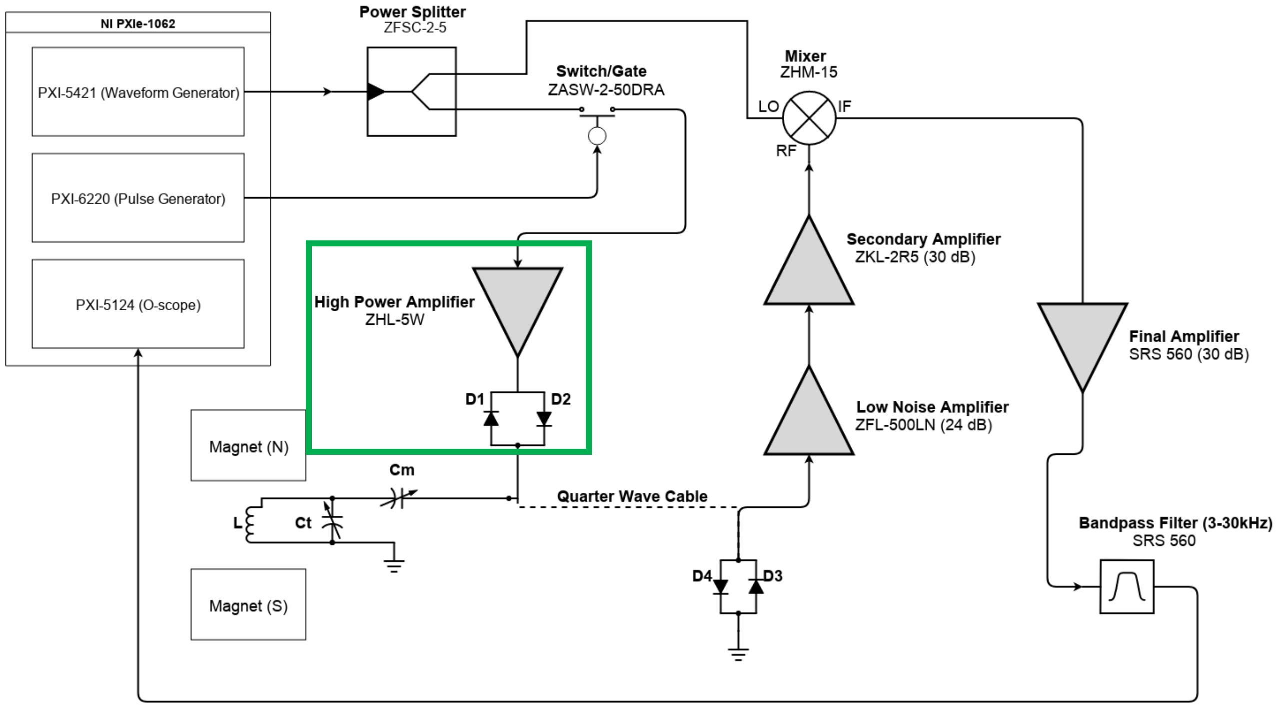

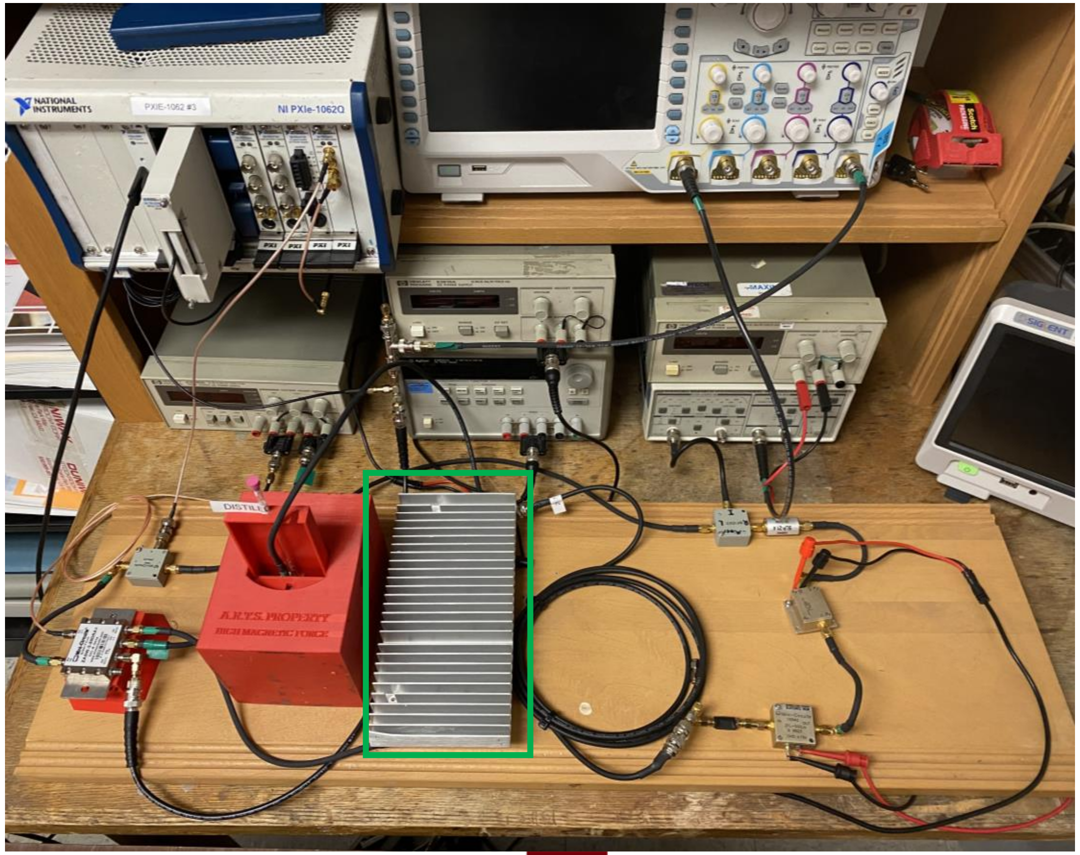

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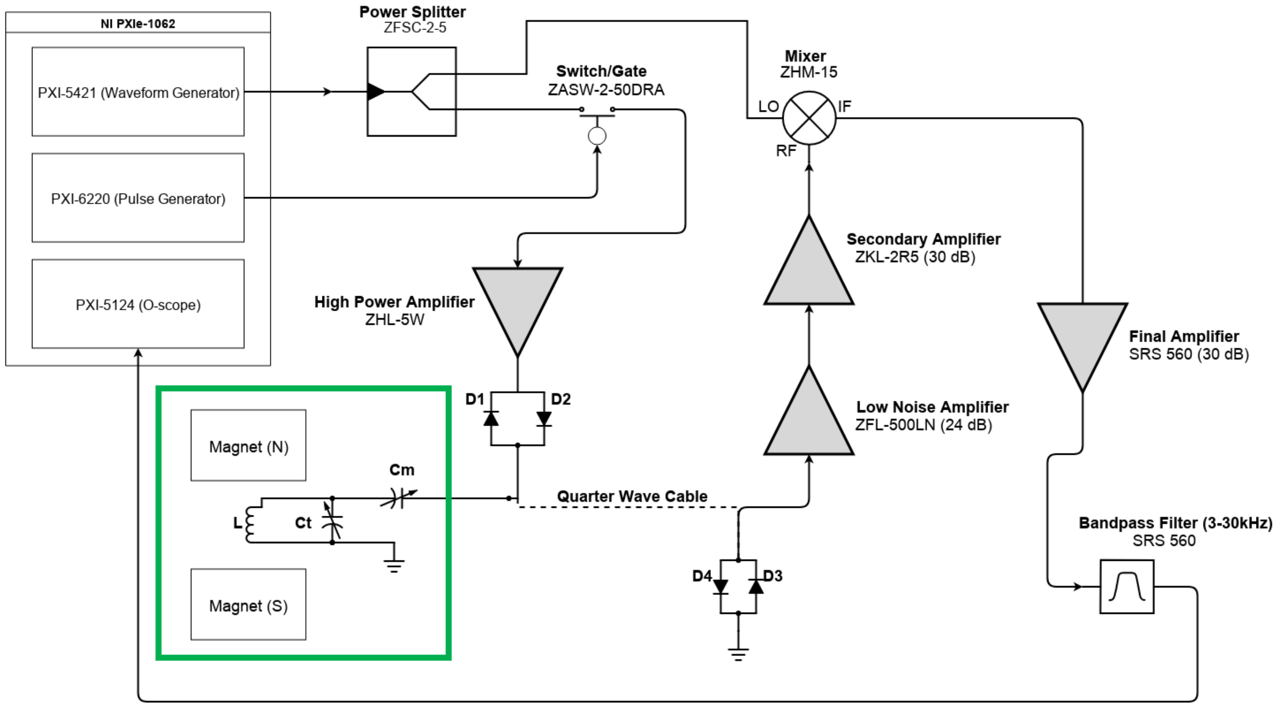

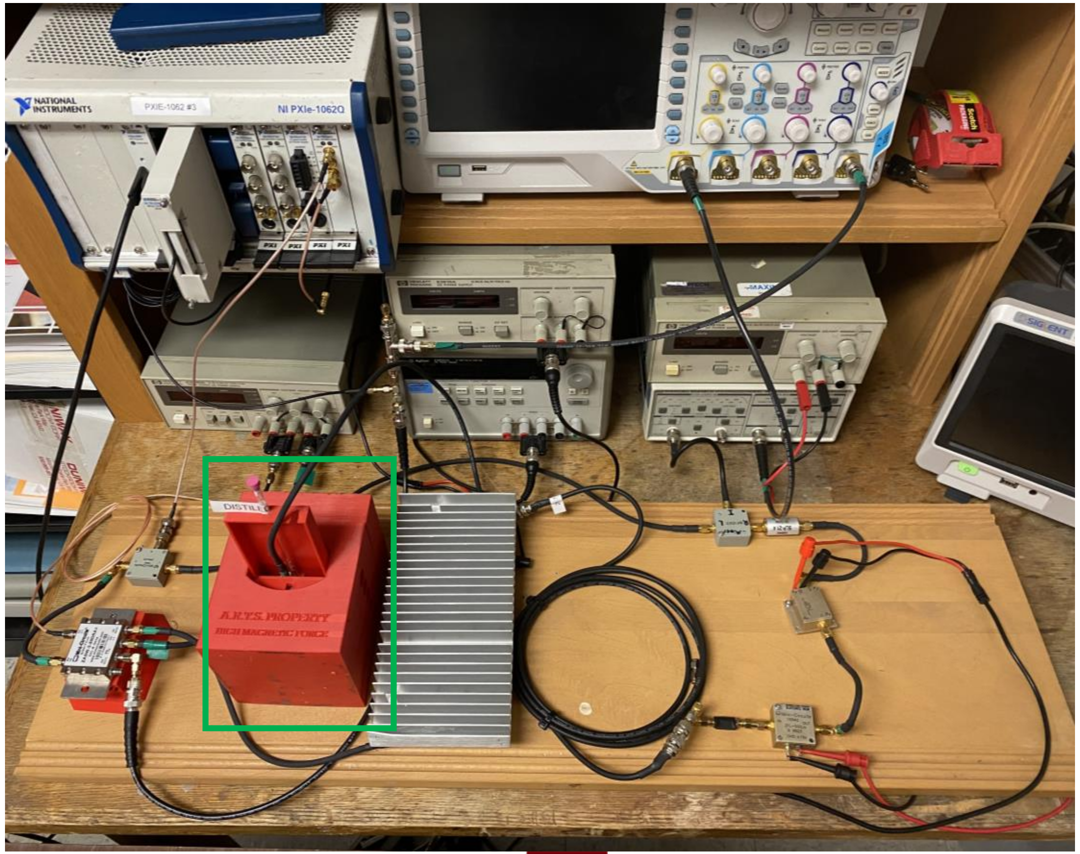

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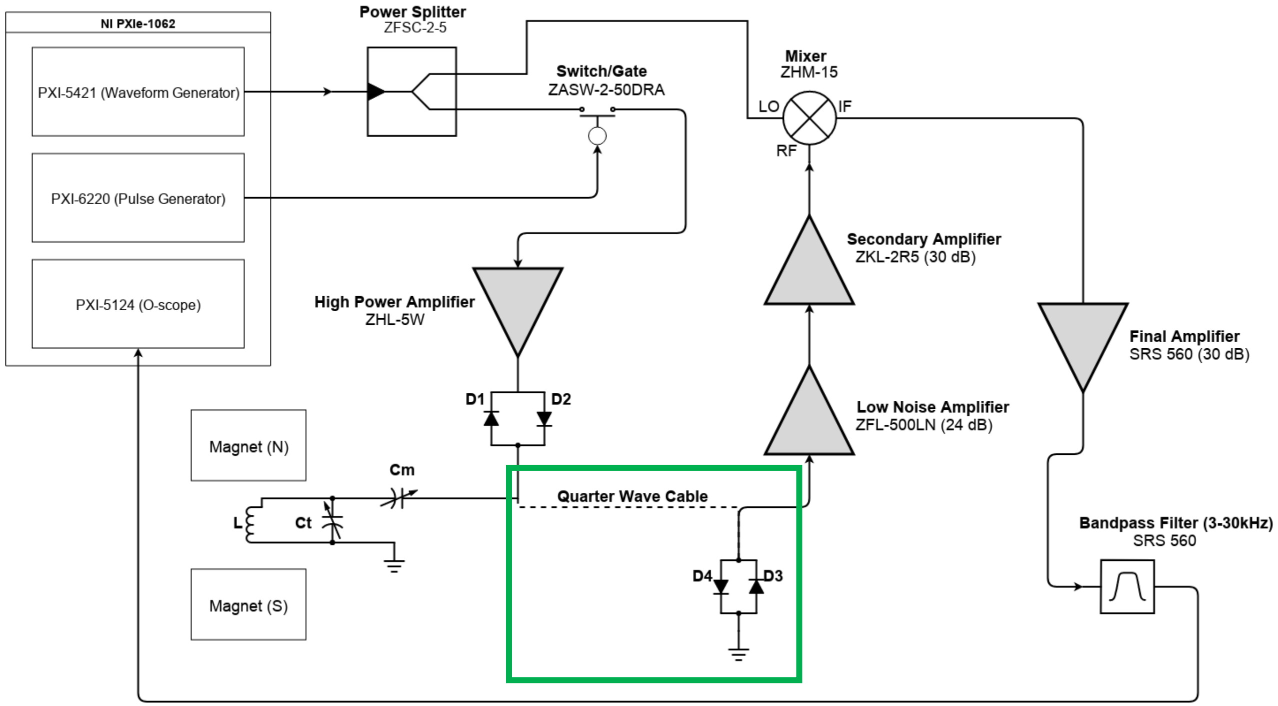

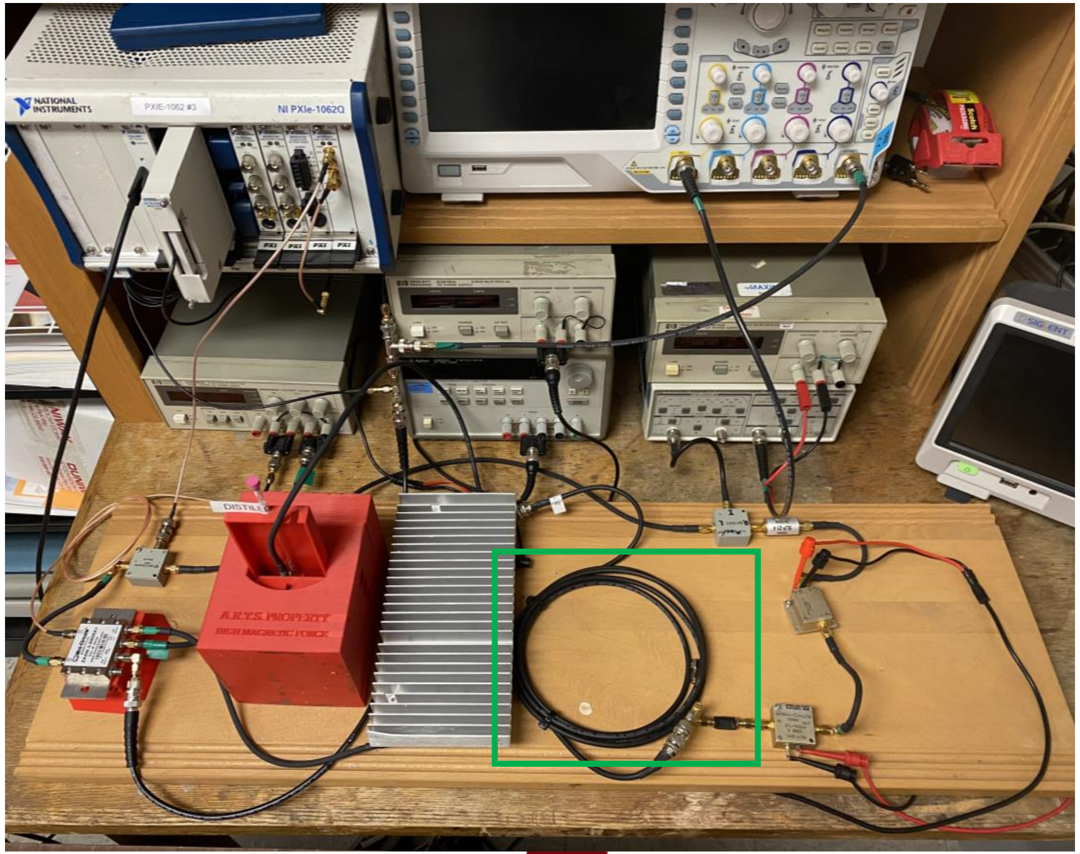

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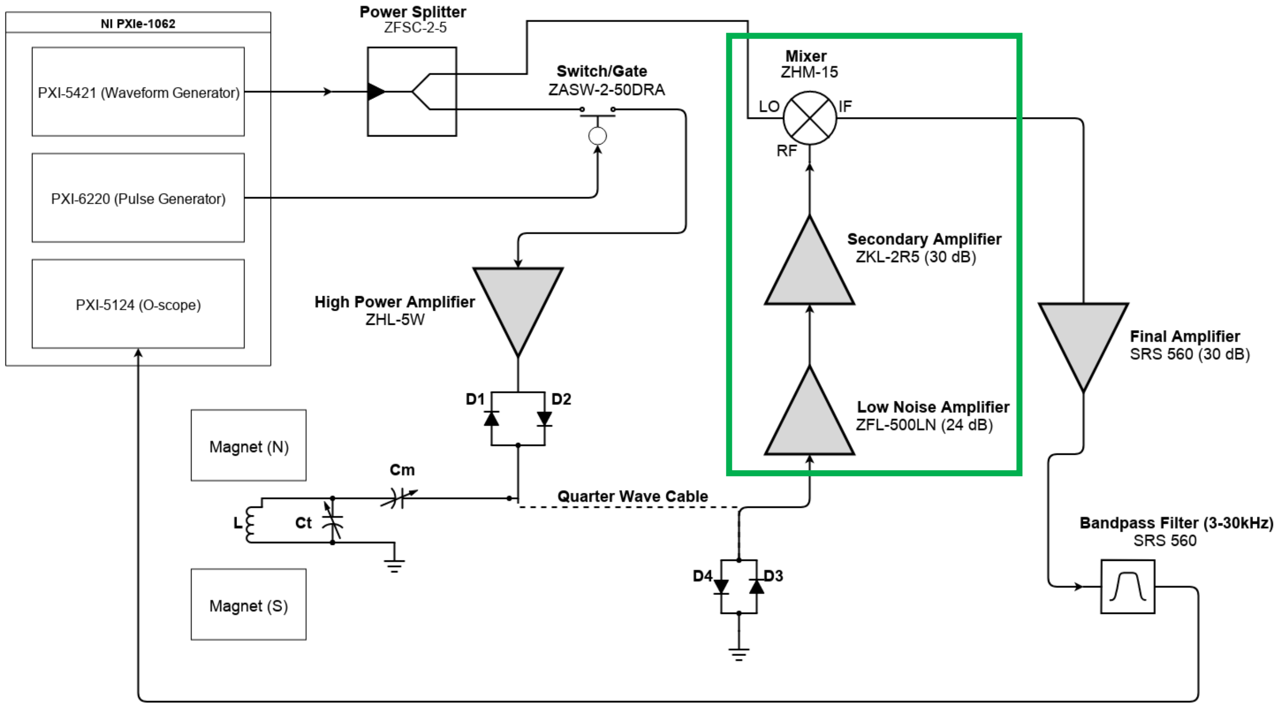

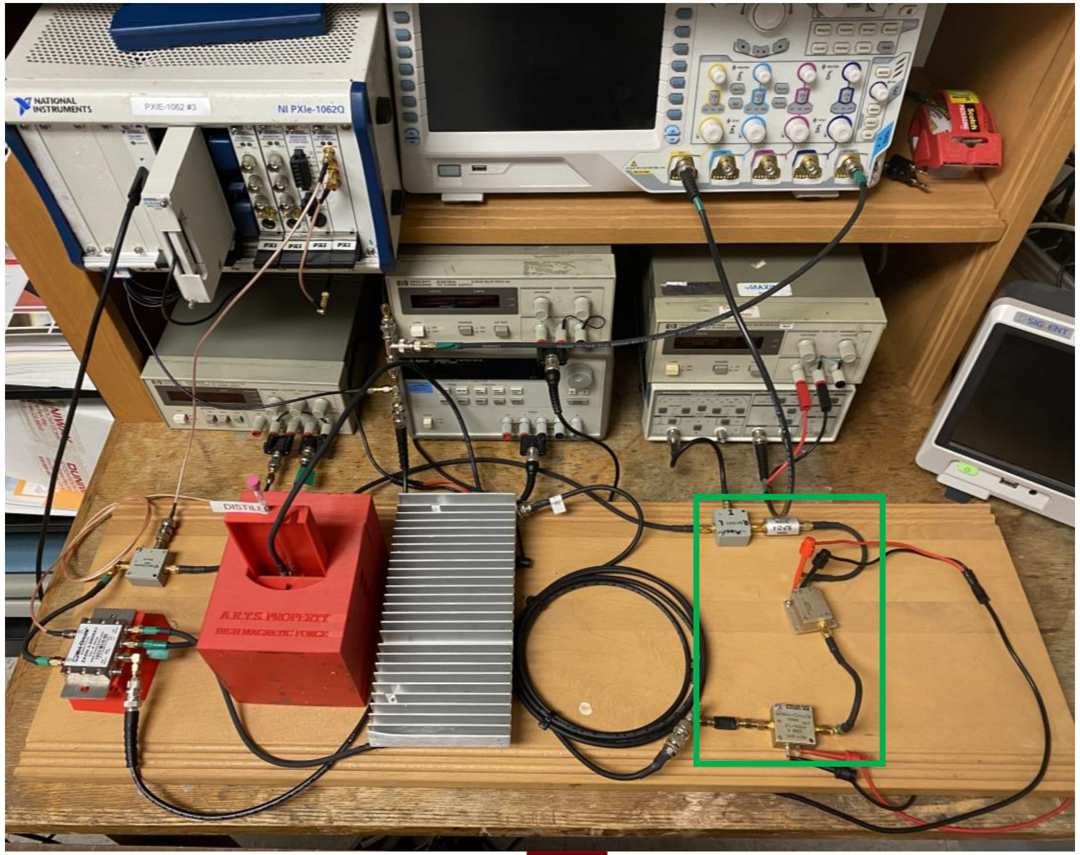

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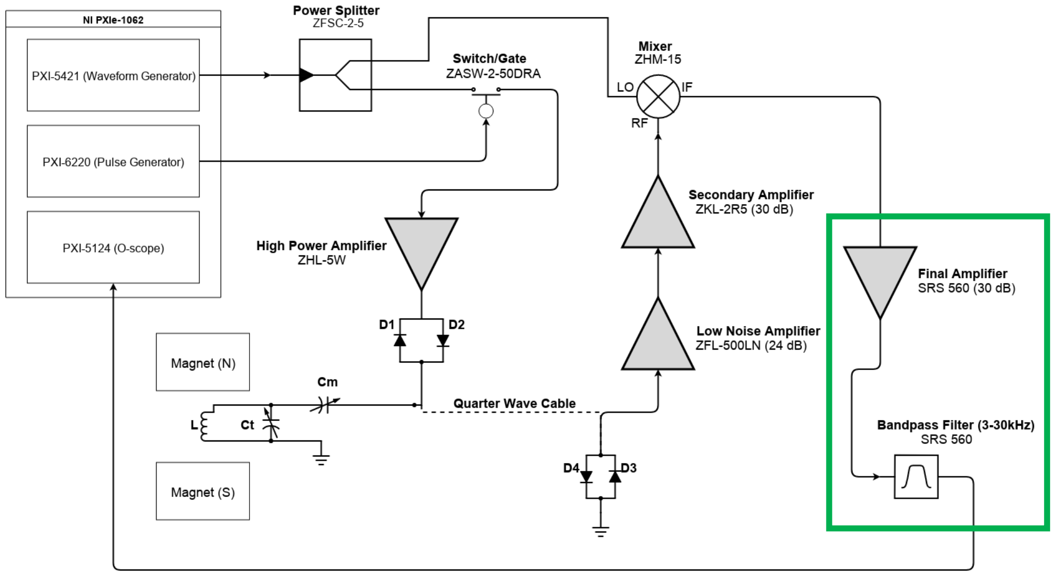

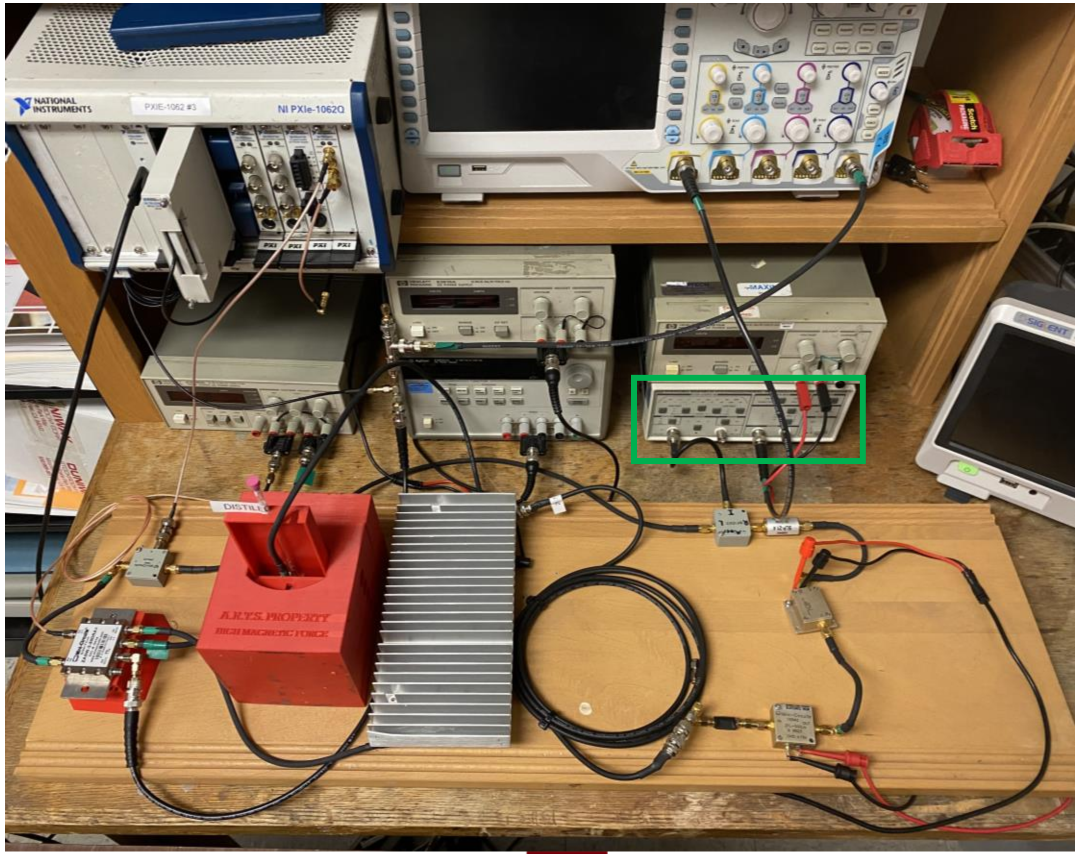

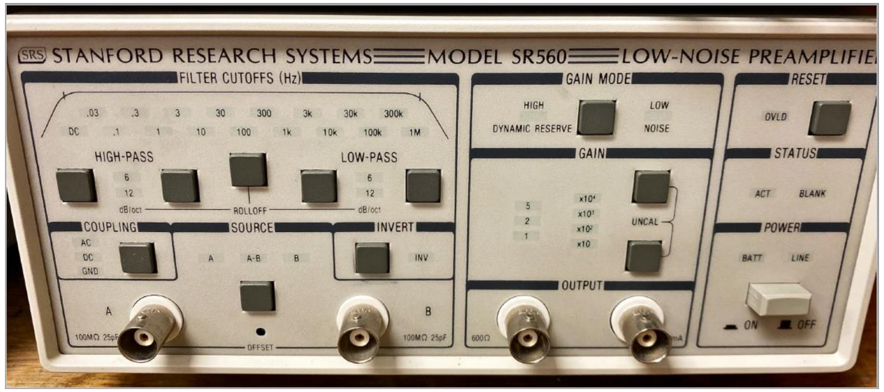

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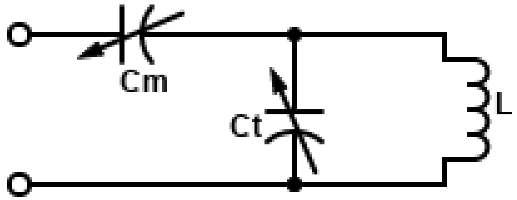
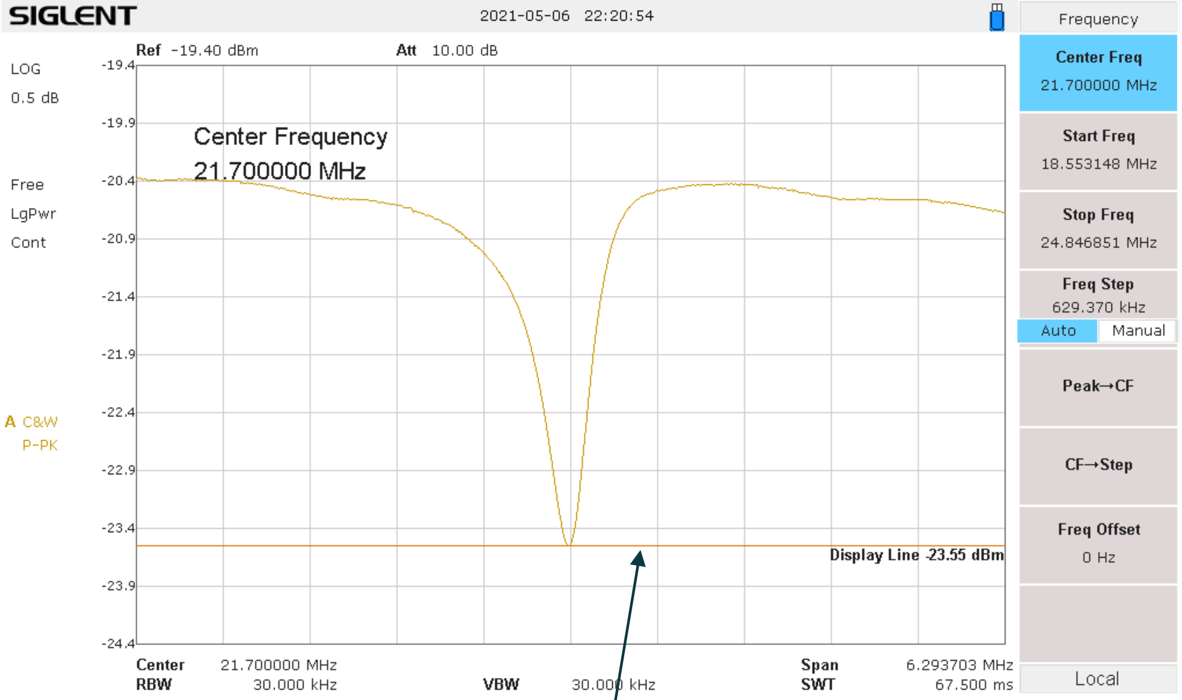
My Setup – Probe Tuning

- The magnetic field strength was measured to be roughly 0.51 T at maximum, so:

$$f = \gamma B_0 = 42.58 * 0.51 \approx \mathbf{21.7\ \mathit{MHz}}$$

- A tracking generator from a spectrum analyzer is used to tune and match the probe
- The variable capacitors are adjusted so that the probe is 50 Ω at the desired frequency





50 Ω reference line

My Setup – Probe Q Factor

- Q factor is a measure of the quality of a coil

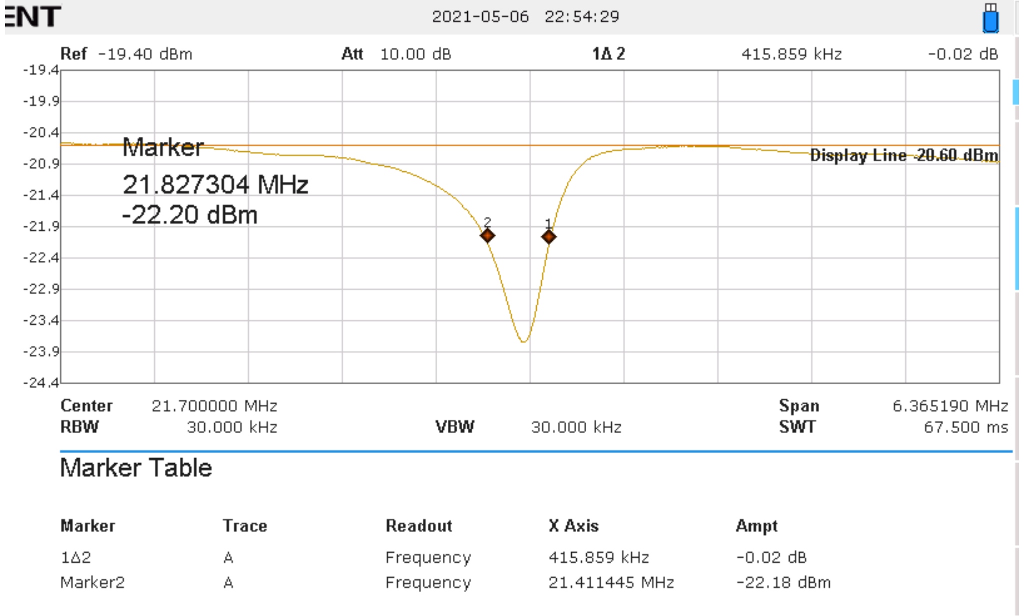
$$Q = \frac{2\pi f L}{R} = \frac{f}{\Delta f} = 2\pi N_{decay}$$

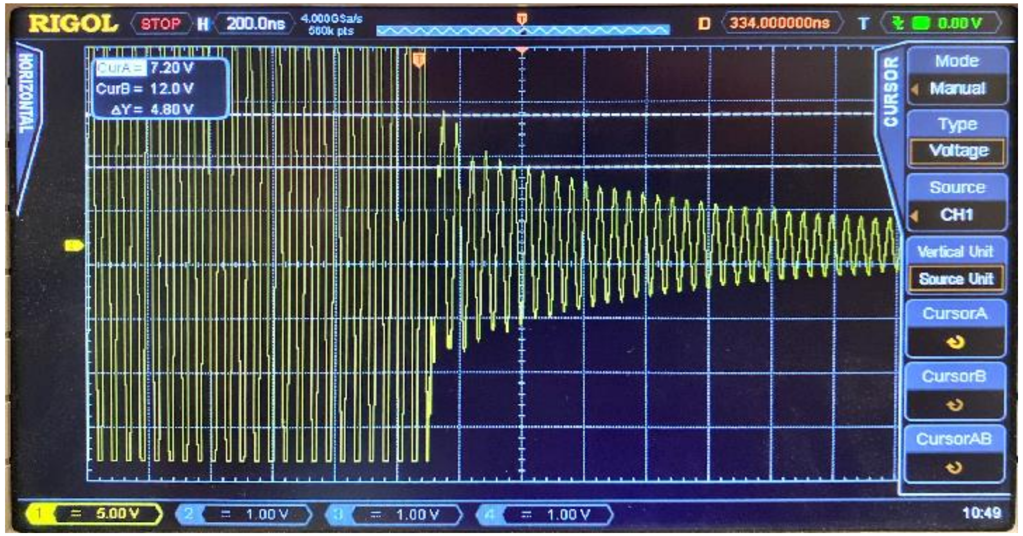
- Using the ratio of center frequency to the full width at half maximum (Δf):

$$Q = \frac{f}{\Delta f} = \frac{21.7\ MHz}{415\ kHz} \approx 50$$

- Using the decay cycles:

$$Q = 2\pi N_{decay} = 2\pi(6.5) \approx 40$$

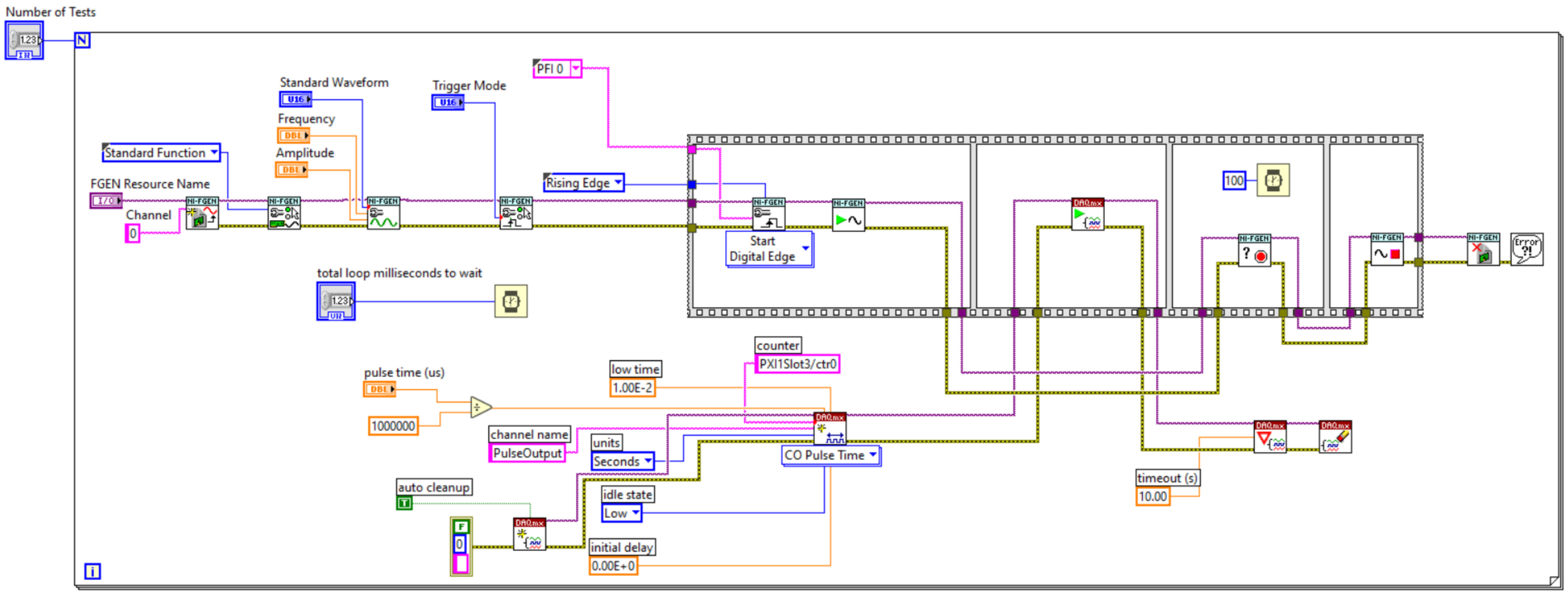




- The Q factor can be used to get an approximation of the coil resistance R
- R can be used to get a theoretical value for the current through the coil
- Knowing the current, the B_1 field in the coil could then be calculated

My Setup – LabVIEW

- Pulse creation, waveform generation, and data acquisition are done using the PXIe-1062
- The pulse goes to the waveform generator trigger, switch TTL input, and o-scope trigger
- The waveform goes to the probe for the pulse duration (through switch) and to the mixer for a duration set by the user (100 ms below) so that it can be mixed with the FID



- The total number of cycles (or pulses) can be controlled by the variable in the top left

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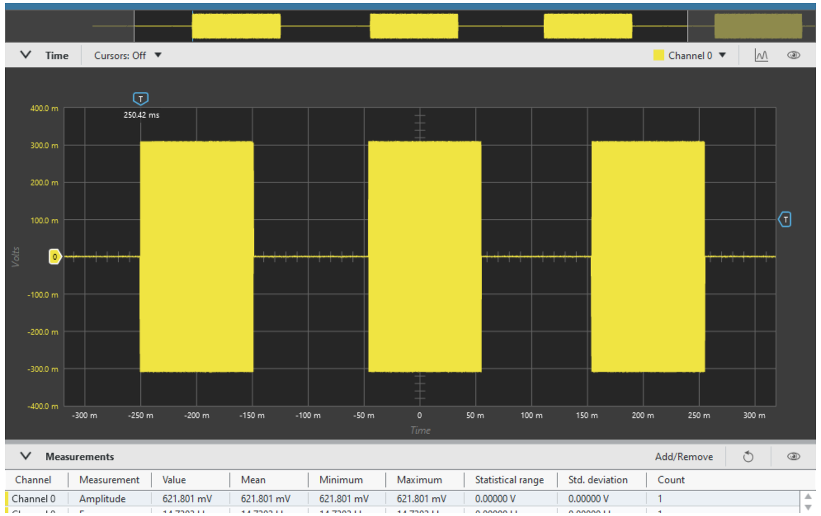
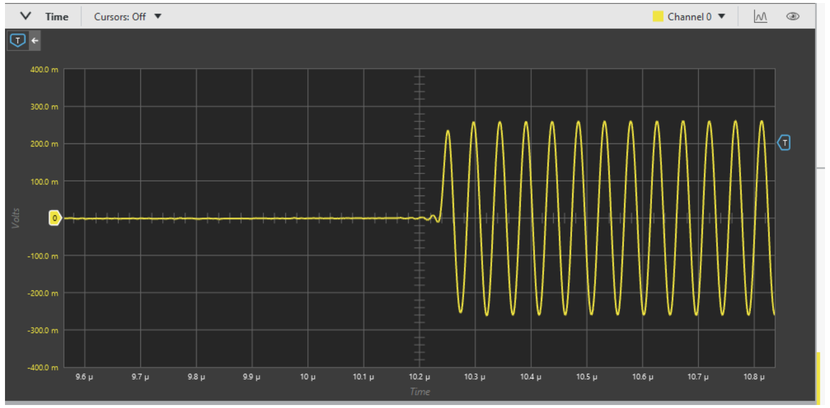
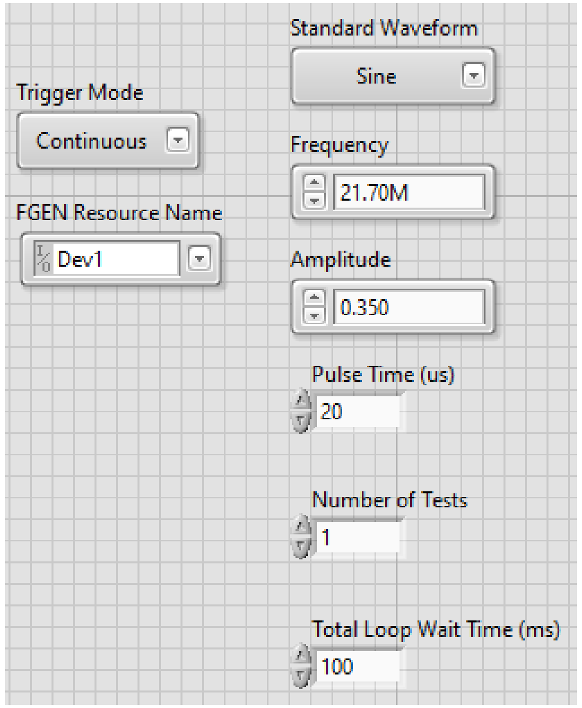
My Setup – LabVIEW

- The front panel allows the user to control all the variables of the pulse sequence
- A sequence of 3 can be seen below, with a duration of 100 ms and a spacing of 100 ms
  - The entire 100 ms wave would be delivered to the mixer, while the probe only receives a small fraction (controlled by 'Pulse Time') since it is gated by the switch
- The pulse **must always start at the same phase**







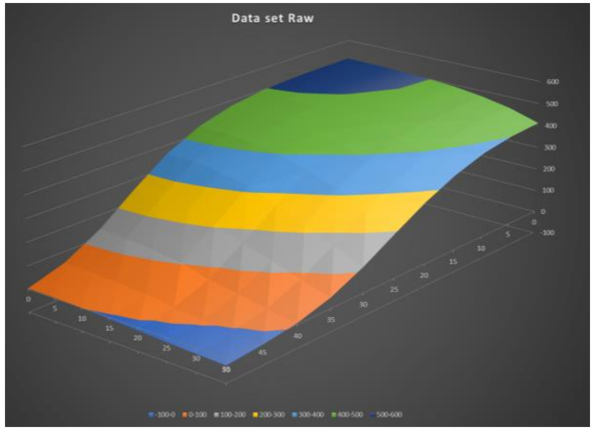
UofSC South Carolina

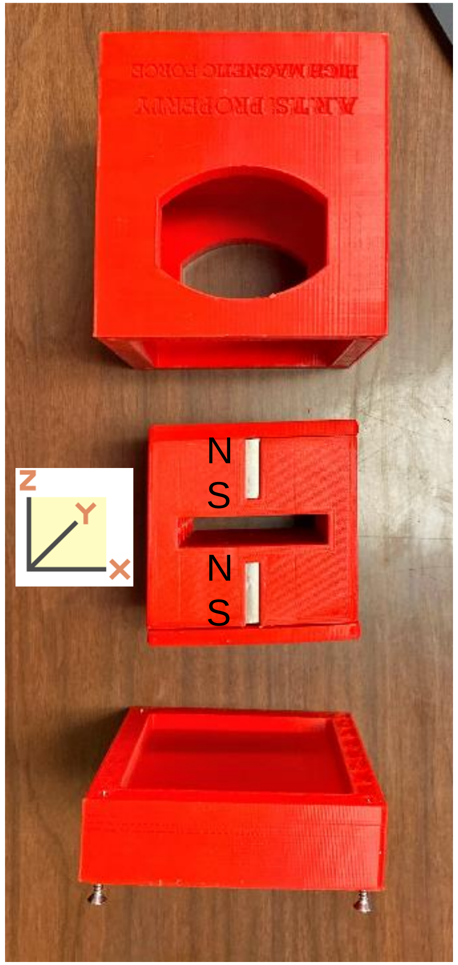
My Setup – Testing

- To increase the signal to noise ratio, a large number of averages are used to display the output
  - Around 200 tests/pulses are used to obtain an averaged signal
  - This reduces the signal to noise ratio
- Have not been able to obtain a response that resembles a characteristic FID (sine wave exponential decay)
- I have gotten “responses” from placing different samples in the probe
  - The output showed noticeable differences when testing different samples and no sample at all
  - However, the output did not have a form that could be characterized as a typical NMR signal
- There are multiple variables that must be in the right balance to get a signal
  - Larmor frequency
  - Pulse duration
  - Pulse power/voltage

Magnet

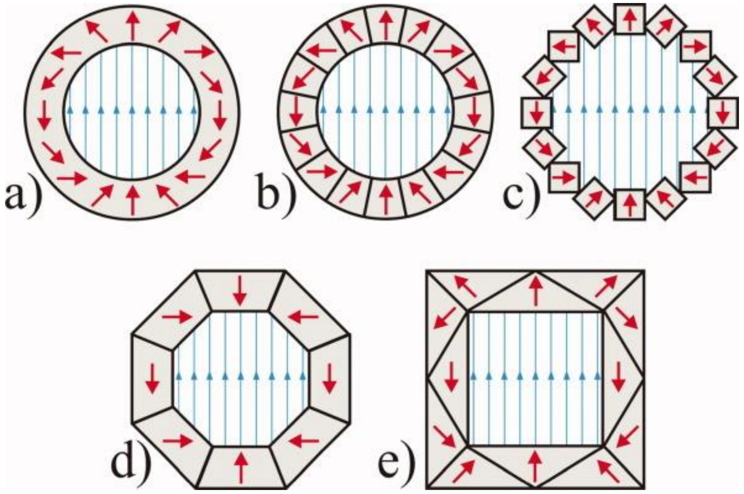
- Magnetic field strength can be remapped along the 3-dimensional space between the magnets
- Previously it seems that mapping was only done for a quarter of the magnet along 2 dimensions (x and y)
  - It was assumed the field is symmetric which is why only a quarter was done
- The coil/probe placement must then be done very precisely so that it is placed in the strongest, most homogenous part of the magnet
  - The current coil placement was not done with a large amount of precision

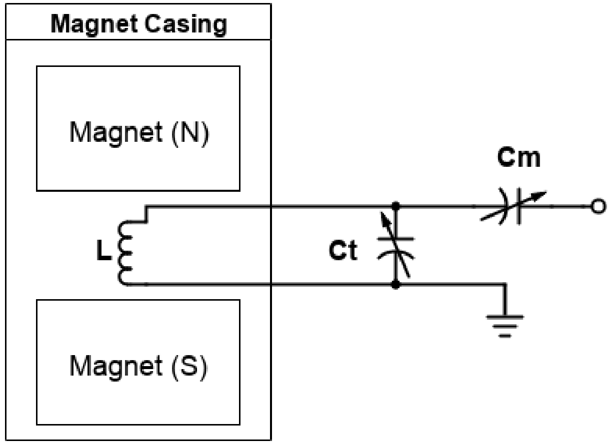


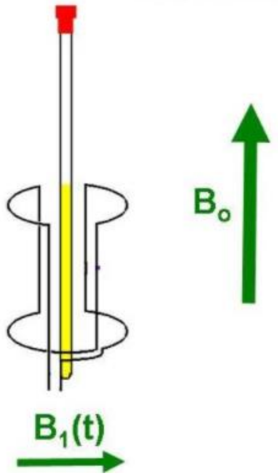


Magnet

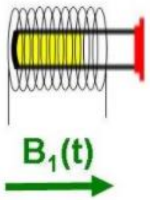
- We have another magnet similar to the current one that could also be mapped to see if it is preferrable
- A Halbach array is another type of magnet design that is a bit more complicated but widely used in NMR
- The Halbach array can be used to produce a very homogenous field
  - Adding layers of high permeability material can also help to increase the field homogeneity







Helmholtz/saddle



Solenoid

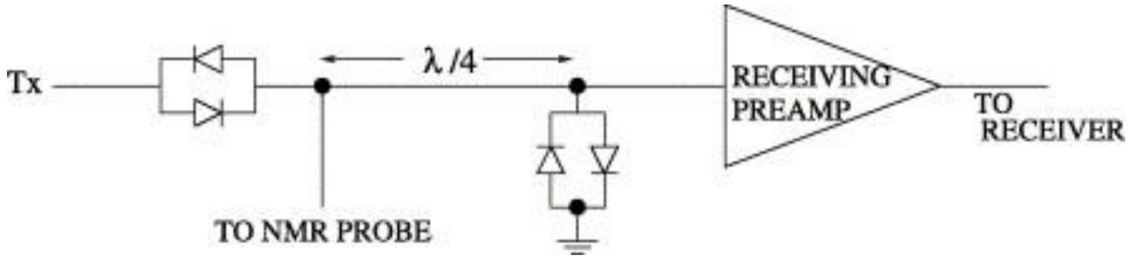
Probe

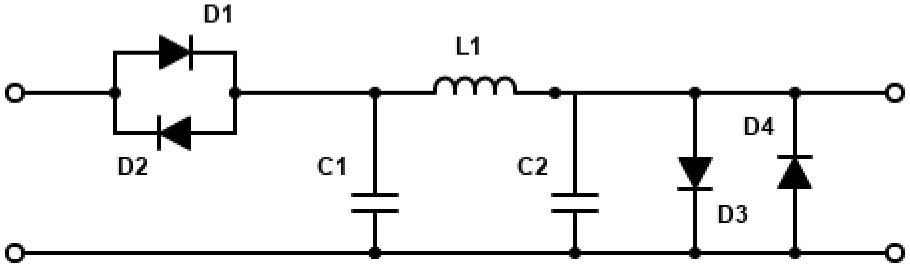
- The entire probe (coil, capacitors, PCB) currently sit inside the magnet when testing
  - This could be causing inhomogeneities around the coil/sample
- Want to redesign so that the coil is fixed in place inside the magnet and the tuning capacitors are just outside of the magnet
  - This would allow the probe to be tuned while inside of the magnet
  - Currently I have to remove the probe, tune it, and then place it back inside
- Other coil designs can be considered, such as a saddle/Helmholtz coil
  - They are relatively easy to fabricate – could be done with copper strips
- Using copper or something similar as shielding around the probe could be useful to reduce stray noise pickup

UofSC South Carolina

Duplexer

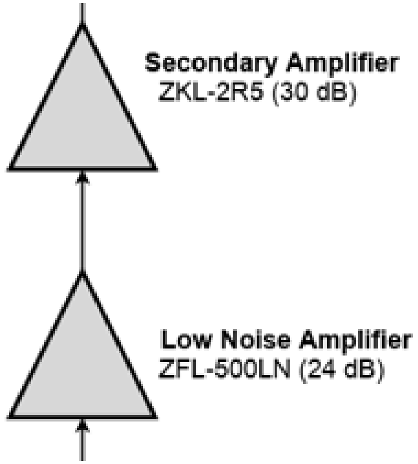
- The quarter wave cable is a simple method of achieving isolation, but there are other options
  - I only have one set of diodes implemented for each gate currently, but adding more pairs could help to increase the isolation
- One way is a pi filter, which accomplishes the same thing, but it uses a combination of capacitors and an inductor
  - Must be tuned so that the input and output impedance is 50 Ω
  - No tuning is necessary for the quarter-wave since it has a characteristic impedance of 50 Ω





Detection Stage

- There are two separate amplifiers currently that boost the initial FID signal
- Probably would make sense to consolidate this to one low noise amplifier to achieve the same gain (≈ 40 dB)
- The total gain should still be about 80 dB, which gets 1 µV amplified to 10 mV
  - The other 40 dB comes from the SRS560 amplifier & filter
- There should not be any problems with the current mixer, but it would be good to make sure we have the best option implemented

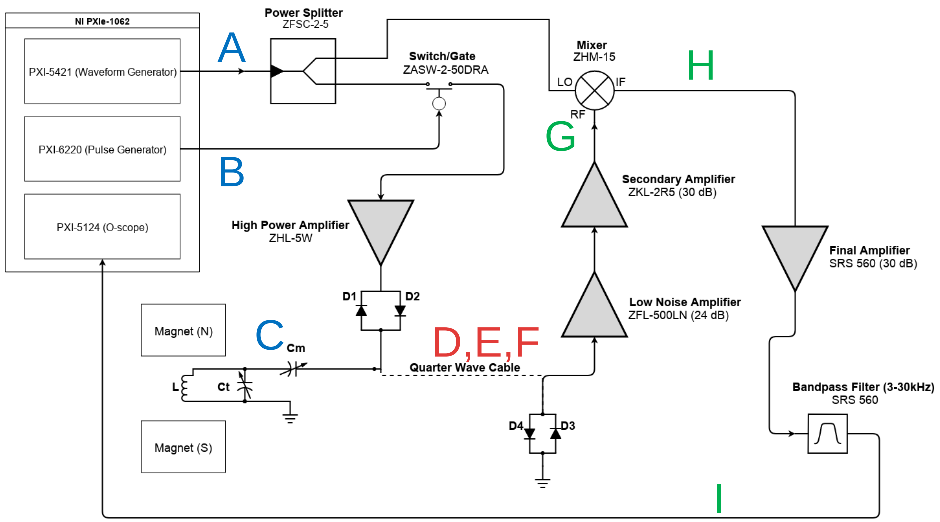


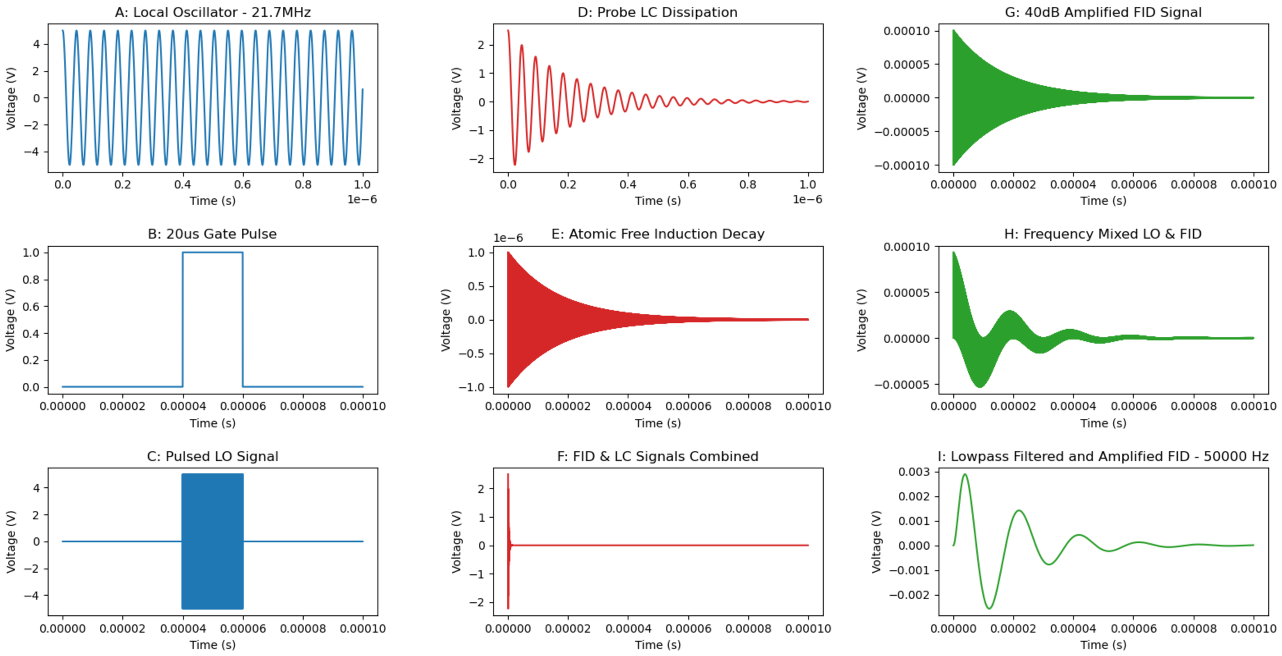
Sample

- The best choice for an easily observable signal is H_2O + CuSO4
- The effect of $CuSO_4$ is to shorten the relaxation time, but it does not affect resonance conditions
- The concentration is usually about 40 mM
  - For a 5 mm tube filled with 60 µL of solution (600 µL total) this is about 0.4 mg
- I have $CuSO_4$, but I need something to accurately measure it so that I can make the appropriate solution
  - Previously I just added $CuSO_4$ by empirical means
- Deionized water by itself can also be used as an initial sample – much longer relaxation time

Simulink & Python Simulations

- Python was used to simulate the waveforms expected at the main junctions of the spectrometer
- This was done awhile back, so an updated simulation would be helpful
  - Simulink would be a good way to do a simulation since it would give a more visual representation of the waveforms at the various circuit junctions





Wrapping Up

- I have started a document/repository of all the NMR papers and documents that have been useful to me
  - Each source contains a relevance ranking, title, short description, and a link if available
- First want to start with the magnet and make sure that we have precise measurements for the field strength and homogeneity across all (or the majority) of the magnet cavity
  - Can map the other magnet and also investigate trying the Halbach design
- The probe design can be adjusted so that coil stays in the magnet and the tuning capacitors are outside
  - Start designing a PCB for the capacitors
  - This could be attached to the magnet casing
- Start working on a Simulink simulation
- I am going to continue testing with various combinations of frequency, pulse width, and pulse power/voltage