Construction of an NMR Polarimeter for a Dynamically Polarized Nuclear Target

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Abstract

Modern nuclear spin experiments rely on scattering from polarized targets. One such target is the solid ammonia target, which is used to measure the spin-structure of the proton. In order to achieve conclusive results with such a technique, accurate polarization measurements of the polarized target must be made. One such option for making said measurements on a solid ammonia target, polarized using dynamic nuclear polarization, is continuous wave nuclear magnetic resonance. The task of this project was to construct an NMR circuit, capable of making these measurements. This involved incorporating legacy code written in the LabView programming language, into the work station for automation of measurements, as well as constructing the physical NMR circuit. The main aspect of the NMR circuit construction was to design and build the Qmeter housing. The Qmeter housing powers the Qmeter as well as thermally regulates the Qmeter. The Qmeter is the essential piece of equipment which allows polarization measurements to be made, by measuring changes in inductance. Results show that the legacy code was successfully incorporated into the Lab machine and is now capable of performing the desired functions. Regarding hardware, the circuit was constructed and the Qmeter housing was built, however the Qmeter was not successfully tuned and therefore, resonance at the desired frequency was not achieved.

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1 Introduction

Modern electron scattering experiments at Thomas Jefferson National Lab, such as the E08-027 experiment set to run in 2011, rely on polarized nuclear targets in order to study the structure of the nucleon. Polarized targets allow experimenters to align the target parallel or anti-parallel to the polarization of the beam line and therefore measure asymmetries. Using asymmetries and scattering from nuclei allows the observer to study nuclear properties such as electromagnetic form-factors and spin structure functions[1]. For cases involving the study of the proton, a convenient target is a frozen ammonia target. Ammonia has a low dilution factor, the number of free protons as compared to the total nuclei. The dilution factor for ammonia is $\frac{3}{18}$. Ammonia is generally selected over other materials with low proton dilution factors because of its high resistance to radiation damage[1].

In order to achieve high proton polarization within the ammonia target the method of dynamic nuclear polarization (DNP) is utilized. DNP is used to polarize the sample much higher than the Boltzmann distribution would allow in thermal equilibrium (TE). Current target technology is at a level where proton polarization can reach levels exceeding 90% [3].

To monitor the polarization during experiments frequent and accurate measurements of the polarization must be made. This is accomplished using nuclear magnetic resonance (NMR) techniques. NMR as a polarimeter is characterized by its low loss rate and accuracy. The purpose of this project was to construct an NMR polarimeter for polarization measurements on a frozen ammonia DNP target.

2 Theory

2.1 Polarization

When subjected to a magnetic field, the magnetic moment, μ, of a particle will align itself with the field. For spin 1/2, it will either be aligned parallel or anti-parallel to the direction of the field. This is possible because spin 1/2 particles have only two possible quantum mechanical orientations, spin up and spin down by convention. The following discussion may be generalized to higher spin particles but for our purposes we will restrict the discussion to spin 1/2 protons.

The polarization of a sample is defined as the ratio of the difference of particle spin directions over the total number of particles.

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \tag{1}$$

The number of particles with spin either aligned or anti-aligned is given by the Botlzmann distribution of the spin states.

$$N_\uparrow = \frac{e^{\frac{\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} \tag{2}$$

$$N_\downarrow = \frac{e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} \tag{3}$$

Inserting the Boltzmann distributions into the polarzation we can produce a simplified equation for the polarization.

$$P = \tanh(\frac{\mu B}{kT}) \tag{4}$$

2.2 Dynamic Nuclear Polarization

Dynamic nuclear polarization is a continuous polarization technique which begins by doping the target material with paramagnetic radicals, at a low concentration $\approx 10^{-4}$ [2]. The material is then cooled to about 1 K in a liquid helium evaporation refrigerator and placed in a 5 T magnetic holding field. Under these conditions at TE, the polarization of the electrons is on the order of 99% while the polarization of free protons is only on the order of 0.4% from equation (4).

Under the influence of the high magnetic field, strong Zeeman splitting occurs, separating the energy levels between electron-proton aligned and anti aligned states.

Because the electron's magnetic moment is about three orders of magnitude larger than the proton's, it experiences much larger splitting. By applying microwave radiation at a frequency $\approx 2.8 \times 10^{10}$ Hz it is possible to induce a spin flip in either the electron or proton, with the required frequencies being ν_e and ν_p respectively. These frequencies correspond to the EPR and NMR transitions in figure 1. Because of spin-spin interactions it is possible to induce the forbidden transitions by using an electron to flip the spin of the proton. When the magnetic moment of the electron flips, it may bring with it the magnetic moment of localized protons. The frequency required to achieve such a flip is $\nu_e + \nu_p$ or $\nu_e - \nu_p$, 140 GHz.

After the flip occurs the electron will relax back to the lower energy state in a time on the order of 10^{-3} s. This is much quicker than the proton, which

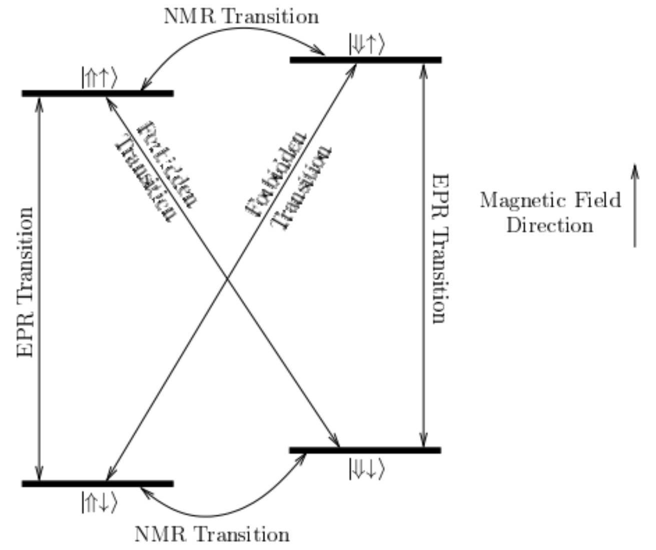


Figure 1: The energy level splitting of an electron proton system under the influence of Zeeman splitting. Reproduced from reference [3]

relaxes back to the lower energy state on the order of 10^3 s [1]. Because the electron relaxes quicker it will become available for another flip, which in turn flips another proton. In time protons will accumulate in a single spin state resulting in the nuclei's polarization propagating outward from each paramagnetic center. This may result in proton polarizations exceeding 90%

2.3 Nuclear Magnetic Resonance

Nuclear Magnetic Resonance (NMR) is the technique used for measuring the polarization of the sample. NMR relies on resonance between two perpendicular magnetic fields to induce a spin flip. Due to the presence of the holding field, the magnetic moment of the proton will precess about the holding field at the Larmor frequency. The Larmor frequency is directly proportional to the strength of the holding field and is described by

$$\omega = \gamma B \tag{5}$$

where γ is the gyromagnetic ratio constant and B is the holding field. For protons $\gamma = 2.675 \times 10^8 \frac{1}{\mathrm{s \cdot T}}$. With a 5 T magnetic holding field the Larmor frequency of protons becomes 212.8×10^6 Hz.

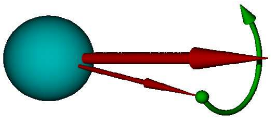


Figure 2: Precession of a magnetic moment about a holding field.

Perpendicular to the holding field is a sinusoidal magnetic field, refered to as the RF field. Resonance occurs when the frequency of the RF field is equal to the Larmor frequency. The occurrence of resonance induces a spin-flip in the protons, they will flip from the aligned state to the anti-aligned state or vice versa. The key piece of equipment which allows us to measure the number of spin-flips (proportional to polarization) is the Qmeter (see section 4.5).

The benefits of NMR include a low loss rate per measurement and fast results. Unfortunately NMR only gives a relative polarization, it is a non-useful measurement unless it is calibrated by using a thermal equilibrium (TE) calibration. A successful calibration will cause the NMR results to be an absolute polarization.

2.3.1 Classical Description

The equation of motion of a particle's spin, $\vec{J}$, in a magnetic field, B_0 is

$$\frac{d\vec{J}}{dt} = \vec{M} \times \vec{B_0} \tag{6}$$

Where $\vec{M} = \gamma\vec{J}$. $\vec{M}$ is precessing about the holding field at the Larmor frequency $\omega = \gamma B$.

$$\frac{d\vec{M}}{dt} = \vec{M} \times \gamma\vec{B_0} \tag{7}$$

When the perpendicular RF field, $\vec{B_1}$, is introduced, the equation of motion of the magnetic moment becomes

$$\frac{d\vec{J}}{dt} = \vec{M} \times (\vec{B_0} + \vec{B_1}) \tag{8}$$

Where $\vec{B_1}$ can be decomposed into vector components rotating about the axis of the holding field, in this case the Z-axis, defined by $\vec{B_0}$.

$$\vec{B_1} = B_1[\cos{(\omega t)}\hat{\imath} + \sin{(\omega t)}\hat{\jmath}] \tag{9}$$

It is useful to place the coordinate system in the rotating frame, rotating about the Z-axis at a frequency defined by the RF fields rotation about the Z-axis, $\vec{\omega}$. To clarify the situation thus far, the holding field is aligned in the $\hat{k}$ direction, the RF field, and thus the rotating frame, is oscillating around the $\hat{k}$ direction in the $\hat{\imath} - \hat{\jmath}$ plane.

It is possible to isolate the effective field.

$$\frac{d\vec{M}}{dt} = (\frac{d\vec{M}}{dt})_r + \vec{\omega} \times \vec{M} \tag{10}$$

$$\frac{d\vec{M}}{dt} = \vec{M} \times \gamma(\vec{B}_0 + \vec{B}_1) + \vec{\omega} \times \vec{M} \tag{11}$$

Distributing γ gives the Larmor frequencies about each magnetic field. Decomposing and grouping the frequencies into their vector components yields

$$\frac{d\vec{M}}{dt} = \vec{M} \times ((\omega_0 - \omega_)\hat{k} + \omega_1\hat{\imath}) \tag{12}$$

This results in an effective field of

$$B_{eff} = \frac{1}{\gamma}((\omega_0 - \omega)\hat{k} + \omega_1\hat{\imath}) \tag{13}$$

Implying that the magnetic moment is precessing about the Z-axis at the angle θ.

$$\tan\theta = \frac{\omega_1}{\omega_0 - \omega} \tag{14}$$

Ramping the frequency of the RF through resonance results in θ flipping through 180 degrees.

2.3.2 Quantum Mechanical Description

The two-state system under the presence of a magnetic holding field and rotating RF field is one for which an exact solution can be achieved. The hamiltonian is

$$\hat{H} = \vec{\mu} \cdot \vec{B} \tag{15}$$

which can be expanded with a rotating RF field of the form

$$\vec{B} = B_0\hat{k} + B_1\cos{(\omega t)}\hat{\imath} - B_1\sin{(\omega t)}\hat{\jmath} \tag{16}$$

and using the Pauli spin matricies

$$\hat{H} = -\frac{\hbar\gamma}{2}[B_1\cos{(\omega t)}\sigma_x - B_1\sin{(\omega t)}\sigma_y + B_0\sigma_z]$$

$$\hat{H} = -\frac{\hbar}{2}\begin{pmatrix} \omega_0 & \omega_1 e^{i\omega t} \\ \omega_1 e^{-i\omega t} & \omega_0 \end{pmatrix} \tag{17}$$

Using the Schrodigner equation it is possible to find exact solutions to the Hamiltonian. The interest here is the probability of a transition taking place from one state to another. The probablitity of a transition is simply the absolute value of the coefficient of the spin-down state squared. If we assume solution of the form

$$\mid \Psi\rangle = a_+ \mid Z,+\rangle + a_- \mid Z,-\rangle \tag{18}$$

Than the probability of a transition is simply

$$P_{a+\rightarrow a-} = \mid \langle Z,- \mid \Psi\rangle \mid^2 = \mid a_- \mid^2$$

$$= \frac{\omega_1^2}{(\omega-\omega_0)^2+\omega_1^2}\sin^2\left(\frac{1}{2}t\sqrt{(\omega-\omega_0)^2+\omega_1}\right) \tag{19}$$

It is apparent that as a frequency sweep is performed and the RF frequency is brought through resonance there will be a maximum probability of spin-flip occuring. In the case of ammonia, NH_3, the resonant frequency is 213 MHz.

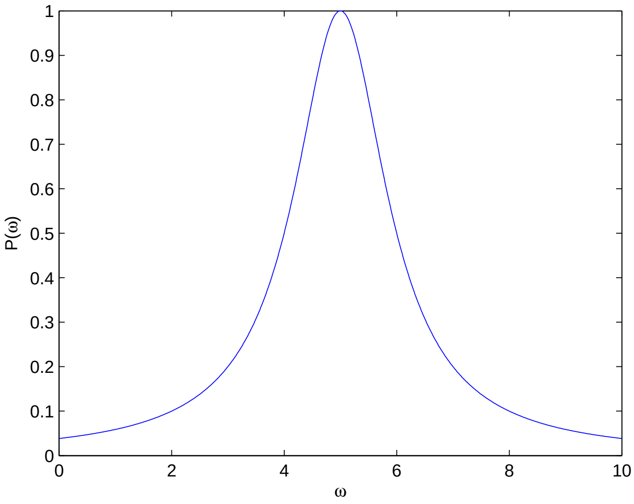


Figure 3: Graph of $P(\omega) = \frac{\omega_1^2}{(\omega-\omega_0)^2+\omega_1^2}$. The time dependant term simply causes oscillations along the curve.

3 Control Software

The control software selected to automate NMR measurements is LabView 2009. LabView is a software package which allows for graphical programming. Using virtual interfaces (VI), it is able to perform such tasks as hardware interface and data acquisition. VIs are written using the LabView graphical programming language and allow simple creation of graphical user interfaces. The VI used to control the NMR circuit at UNH was written by Paul McKee and acquired from the polarized target group at UVA.

The VI is actually a suite of subVIs, each with individual functions, interfaced using transfer control protocol (TCP) that communicate with the polarization control panel (PDP). The PDP is the workstation that allows the user to control every function of the target and NMR processes including, frequency sweeps, data acquisition, microwave control, target motion control, slow controls, the superconducting magnet, target temperature monitor, signal analysis, and the target event builder. A benefit of the suite relying on TCP is that different machines may be used to control different functions of the target, assuming a wireless GPIB router is available. For the purposes of NMR, only frequency sweeps, data acquisition, and signal analysis will be discussed in any further detail, a flow diagram of the VI involved in these processes may be seen in figure 4.

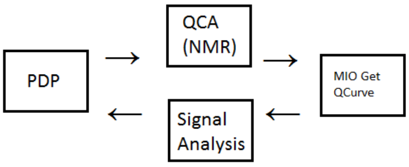


Figure 4: Flow chart of central NMR VIs.

The first step in acquiring any NMR measurements using PDP is to set PDP to NMR tune and tune the NMR circuit using the phase adjustments on the Qmeter (see section 4.6).

With the circuit tuned properly it is necessary to establish a baseline. A baseline sweep is performed off resonance by either changing the strength of the holding field or sweeping the RF field away from 213 MHz. The purpose of the baseline is to account for the RF signal returning through the pickup coil (the RF coil acts as the pickup coil), circuit noise, and background signal from random motion within the target material. It is necessary to make a new baseline anytime any change is made in the NMR circuit.

With a sufficient base line PDP may be used to perform an actual NMR measurement. There are three main phases to the NMR measurement, frequency sweeps, data acquisition, and signal analysis.

3.1 Frequency Sweeps

Frequency sweeps are performed by setting the function generator to the resonant frequency, 213 MHz, and using external inputs to modulate the frequency (FM). The output RF of the function generator is modified by scaling the resonant frequency proportional to the voltage sent to the external input on the function generator. The voltage used to FM the function generator is created digitally using the *MIO Get QCurve.vi* program. *MIO Get Qcurve.vi* communicates with the PCI-MIO-16XE-10 card using the Traditional DAQ set of drivers from national instruments and is able to create a digital to analogue (DAC) voltage. The voltage is output by constructing a piecewise triangle wave consisting of 500 individual steps. Each step results in an output voltage of strength proportional to the amplitude of the triangle wave. Because the triangle wave has a frequency of 15287 Hz, an effective continuous wave is created resulting in the RF signal being continuously modulated. The amplitude of the triangle wave is chosen to FM the signal by $\pm 0.4\%$ or $\pm$ 852 KHz. A triangle wave is used so that the RF output is linearly modulated beginning below resonance, swept through resonance, past resonance, and back down again. During each polarization measurement made by PDP, 200 sweeps are performed. In summary the PDP uses the MIO card to create a voltage which modifies the output frequency of the function generator which in turn may induce a spin flip.

$$\text{PDP} \rightarrow \text{MIO} \rightarrow \text{Voltage} \rightarrow \text{RF frequency} \rightarrow \text{Spin Flip} \tag{20}$$

3.2 Data Acquisition

Along with modulating the frequency of the function generator the *MIO Get QCurve.vi* is also responsible for storing voltages read by the MIO card. The data acquisition (DAQ) is written using Traditional DAQ drivers from National Instruments. It uses the Analogue In suite of VIs to configure the hardware and record signals whenever the internal trigger is detected using jumpers located on the BNC 2090 breakout panel. Because it is written with internal triggers to initiate the DAQ, a signal is recorded every time the frequency is modulated. Specifically, the Analogue Out section of *MIO Get QCurve.vi* moves one rung up the piecewise triangle wave, modulating the frequency by one unit (as discussed in section 3.1). This creates a trigger which activates the Analogue In section of the code allowing for a signal to be read in from the BNC 2090 and stored in an array. This ensures that a signal is recorded for every point along the frequency sweep, creating a time uniform array of data to be analyzed for polarization. Because the frequency sweep is ran 200 times and lasts approximately 14 seconds, so too does the DAQ. Each run is saved in the array for a total of 200 runs and averaged to produce the data that will be analyzed. The DAQ response looks like

$$\text{FM} \rightarrow \text{Trigger} \rightarrow \text{Signal In} \rightarrow \text{Store signal} \rightarrow \text{FM} \tag{21}$$

3.3 Analysis

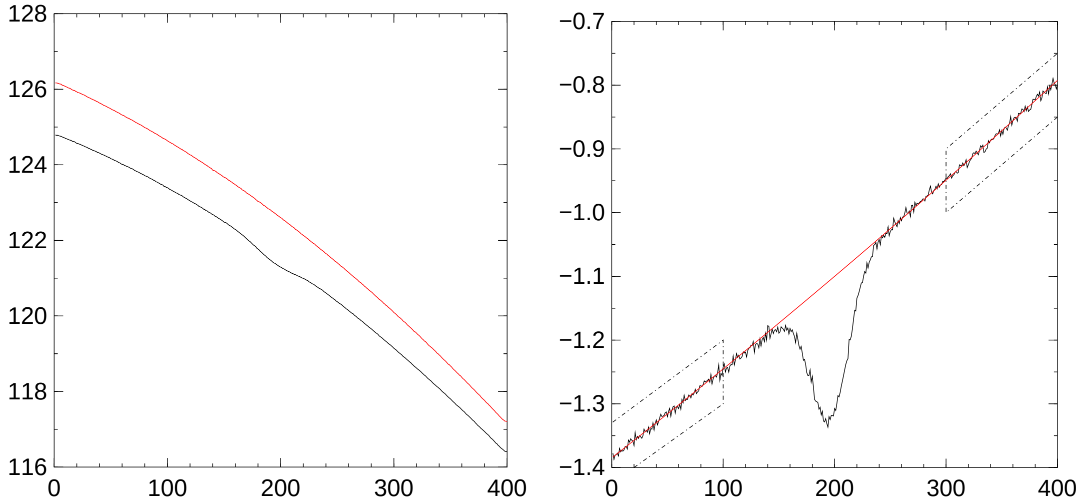
Analysis of the data acquired in the DAQ phase of the *MIO Get QCurve.vi* is then read in through the *Signal Analysis.vi.* The signal is conditioned through four phases before it is converted to a polarization using the calibration constant (CC), see figure 5. First, the baseline is subtracted from the raw data, resulting in a peak with "wings". The second stage of signal conditioning consists of performing a second order polynomial fit on the "wings" of the data of the form

$$\text{Signal} = A\omega^2 + B\omega + C \tag{22}$$

The fit results in good correlation with the "wings" of the data but high residuals at the peak. Subtracting the polynomial fit from the data yields a single peak.

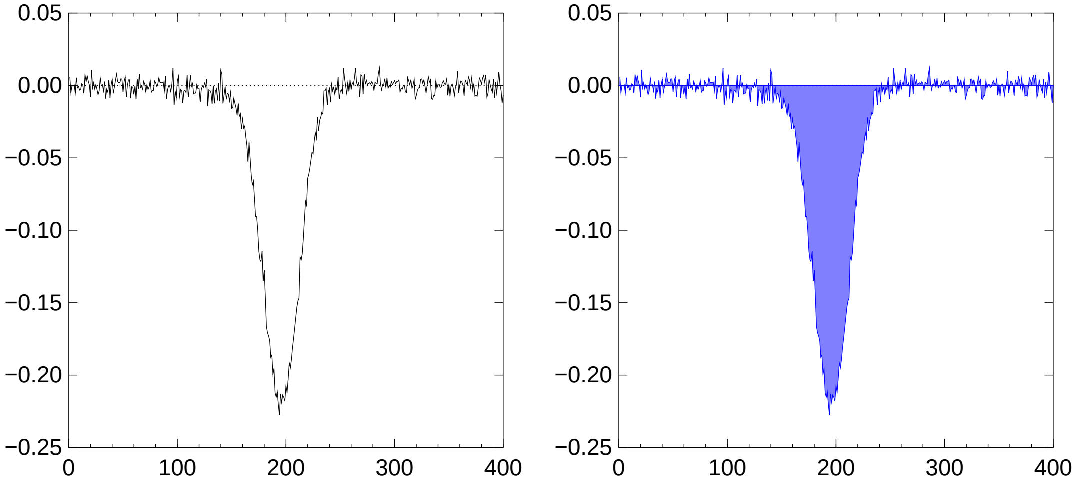
The final stage of signal analysis is to integrate the area under the peak. This tells us the total signal due to the flipping of spins at resonance. A polarization is then achieved by multiplying by the CC which has units of $\frac{\%pol}{mV}$.

$$\text{Pol} = \text{CC} \times \text{Area}_{\text{peak}} \tag{23}$$



Raw data and baseline

Polynomial fit to wings



Subtraction of polynomial fit

Integration of curve

Figure 5: Process of signal analysis. Reproduced from reference [4]

3.3.1 Thermal Equilibrium Calibration

Uncalibrated, the polarization given by PDP is simply a relative polarization. In order to measure an absolute polarization the system must be calibrated. This is because the polarization is linearly proportional to the area under the signal vs ω curve. To find the constant of proportionality, known as the calibration constant, a TE measurement must be made and compared to the calculated TE polarization using equation (4). In other words, the area under the signal will be scaled to equal the TE polarization, which is known from equation (4).

$$P = \mathrm{CC} \times \mathrm{Area}_{\mathrm{signal}} \tag{24}$$

Using equation (4) to calculate P_{TE}, we can calculate the CC.

$$CC = \frac{P_{\mathrm{TE}}}{\mathrm{signal}_{\mathrm{TE}}} \tag{25}$$

4 NMR circuit

The PDP is the central control console which is responsible for automating the hardware. From PDP signals are used to control a function generator, responsible for frequency sweeps, and the data acquisition, which involves reading the output from the Qmeter. The Qmeter is the central piece of equipment which allows us to measure the response of the NMR circuit to the polarization of the sample.

The NMR circuit consists of five main components, the workstation, function generator, BNC 2090 Breakout, Qmeter Box, and pickup coil. A circuit diagram may be seen below in figure 6.

4.1 Work Station

The workstation being used in DeMeritt 103 is a Dell Inspiron desktop running Windows XP. It is equipped with two non-standard PCI cards. PCI cards allow the computer to communicate with external hardware. The first PCI card is a National Instruments PCI-GPIB card. It is used to control the function generator, using GPIB to modify characteristics of the signal, such as frequency and amplitude, which change depending on the channel being used. GPIB (General Purpose Interface Bus) is a IEEE standard used to communicate with automated test equipment. The second PCI card is a National Instruments PCI-MIO-16XE-10 card. This card's functions include; frequency modulation of the function generator and data acquisition.

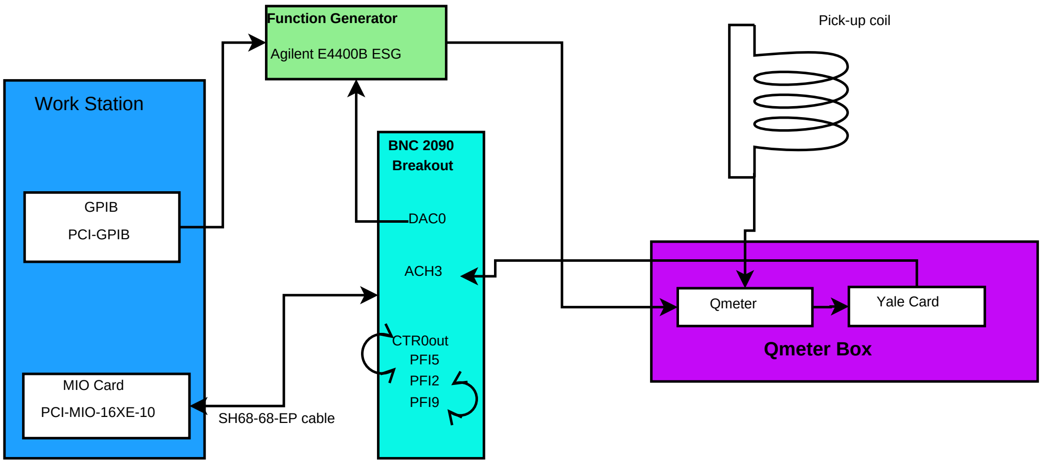


Figure 6: Schematic of the NMR circuit.

4.2 BNC 2090 Breakout

The BNC 2090 Breakout is another National Instruments product. It acts as a breakout board for the pins on the PCI-MIO-16XE-10 card. The connections used in the circuit are the ACH3 and DAC0. The DAC0 is the digital to analogue channel which outputs a voltage designed to frequency modulate the function generator (see section 3.1). The ACH3 is the analogue to digital channel where data acquisition takes place from the Qmeter.

The BNC 2090 is also used as the hub where the internal triggers are sent and received to facilitate DAQ. Jumpers are placed between, CTR0out and PFI5, and PFI9 and PFI2 (see section 3.2).

4.3 Function Generator

The function generator used is an Agilent model E4400B ESG, connected to the workstation via a GPIB cable. This connection is used to control the output signal strength and base frequency. To clarify, when it is desired to perform NMR on the proton, the frequency is set to 213 MHz. It is also connected to the DAC0 channel of the BNC 2090 via a BNC cable to the EXT1 input on the face of the function generator. The external input is where signals are received to FM the RF signal of the function generator. This is the input that is responsible for ramping the frequency up and down from the base frequency of 213 MHz. Finally the RF output is connected to the Qmeter reference channel (port B on figure 8).

4.4 Pickup Coil

The pickup coil is constructed using standard copper magnetic wire and is connected to a cable with a foam dielectric interior. The cable is attached to the Qmeter using SMA connectors and is cut to a length of $\frac{\lambda}{2}$, where λ is the wavelength of the first harmonic standing wave in the cable. It is cut to this length because the signal must travel the length of the wire twice, resulting in it being in phase with the reference signal when it is at 213 MHz, upon its return to the Qmeter.

4.5 Liverpool Qmeter

Dynamic nuclear polarized targets allow the option of frequent polarization measurements. A common technique used to measure the polarization of such targets involves measuring the response of a tuned RLC circuit as a function of frequency. One method of studying the response of such a circuit is by measuring changes in the output voltage as a function of frequency. The response dictates the output voltage and is known as the Q factor. The Q factor is defined as the energy stored over the energy lost per cycle.

The essential piece of equipment which allows us to study the NMR signal is called a Q meter. The Q meter is a highly tunable precision instrument which, in conjunction with the pick-up coils, acts as a tunable RLC circuit. The main components of the Qmeter are a balanced ring modulator, a full wave diode rectifier, and a tunable capacitor.

4.5.1 Principles of Q meter

The Q meter is an RLC circuit, meaning it has a complex impedance.

$$Z = i\omega L - \frac{i}{\omega C} + R \tag{26}$$

The inductance of the circuit comes from the pick-up coils. The inductance of the pick-up coils is dependent upon the filling factor, η, and the susceptibility, χ, of the material within the coils.

$$L = L_o(1 + 4\pi\eta\chi) \tag{27}$$

Where L_o is the normal inductance due to the magnetic field and area of the loop. When a RF field at the NMR frequency is applied to the material within the coils and a spin flip is achieved, a complex term of the susceptibility is introduced.

$$\chi = \chi' - i\chi'' \tag{28}$$

The complex term comes from the flipping spins and can be thought of as the phase lag of the spins behind the RF field. The new complex susceptibility modifies the inductance, causing the impedance to become

$$Z = iA + R + L_o \omega 4\pi\eta\chi'' \tag{29}$$

where A is the complex term of the impedance. Because the response of the circuit, Q factor, is defined as

$$Q = \frac{\omega L}{R} \tag{30}$$

with R begin the resistance, our Q factor becomes

$$Q = \frac{\omega L}{R + L_o \omega 4\pi\eta\chi''} \tag{31}$$

This implies that when resonance is achieved and a maximum spin flip occurs, ie χ'' is a max, the response of the signal is reduced. This may be seen in figure 5 as the "dip" in the Raw data line.

The magnitude of the "dip" is proportional to χ'', which is proportional to the number of spin flips, and therefore the polarization of the cell. By subtracting the baseline signal from the signal with spin flips a lorentzian is produced. The area under the lorentzian is proportional to the magnitude of χ''. Therefore there is a linear relation between the area under the curve and the polarization of the cell.

$$P \propto \int_{-\infty}^{\infty} \chi''\, d\omega \tag{32}$$

4.5.2 Circuit Overview

The reference signal is fed in through input B (see figures 7 and 8). From input B the reference signal is sent through a series of attenuators and op amps as well as a phase cable in order to properly condition the signal for the modulator.

The pick-up coil is sent through the $\lambda/2$ cable which is connected to input H. The pick-up coil signal is first sent through the tunable capacitor where it is then sent through op amps and attenuators to condition the signal. It is then incident upon the splitter which sends the signal to the modulator and the diode. In order to tune the circuit, it is necessary to include a means of reading the modulator and diode signals before they are sent through the post detector stage.

The reed switch is placed in parallel with the tuning capacitor as a means to ground the signal. The nature of the Q meter dictates that there must be a different Q meter assigned to each channel. In order to avoid feedback and noise the reed switch is activated to ground the Q meter. It is necessary that all but the current channel being used are grounded.

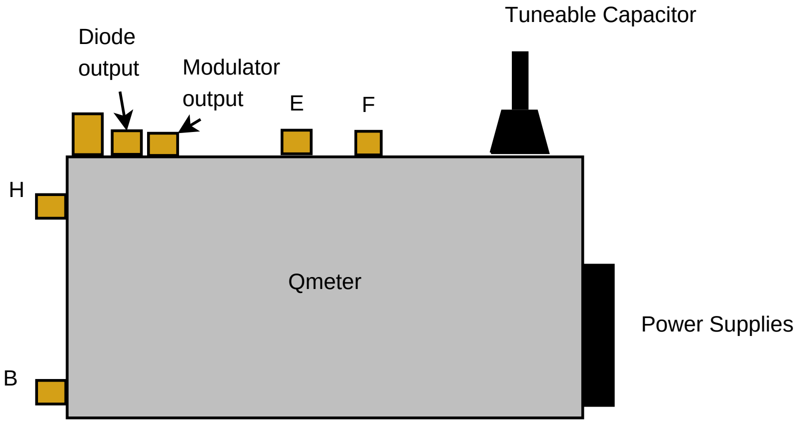


Figure 7: Exterior inputs on Qmeter box. Compare to inputs on circuit diagram in figure 8

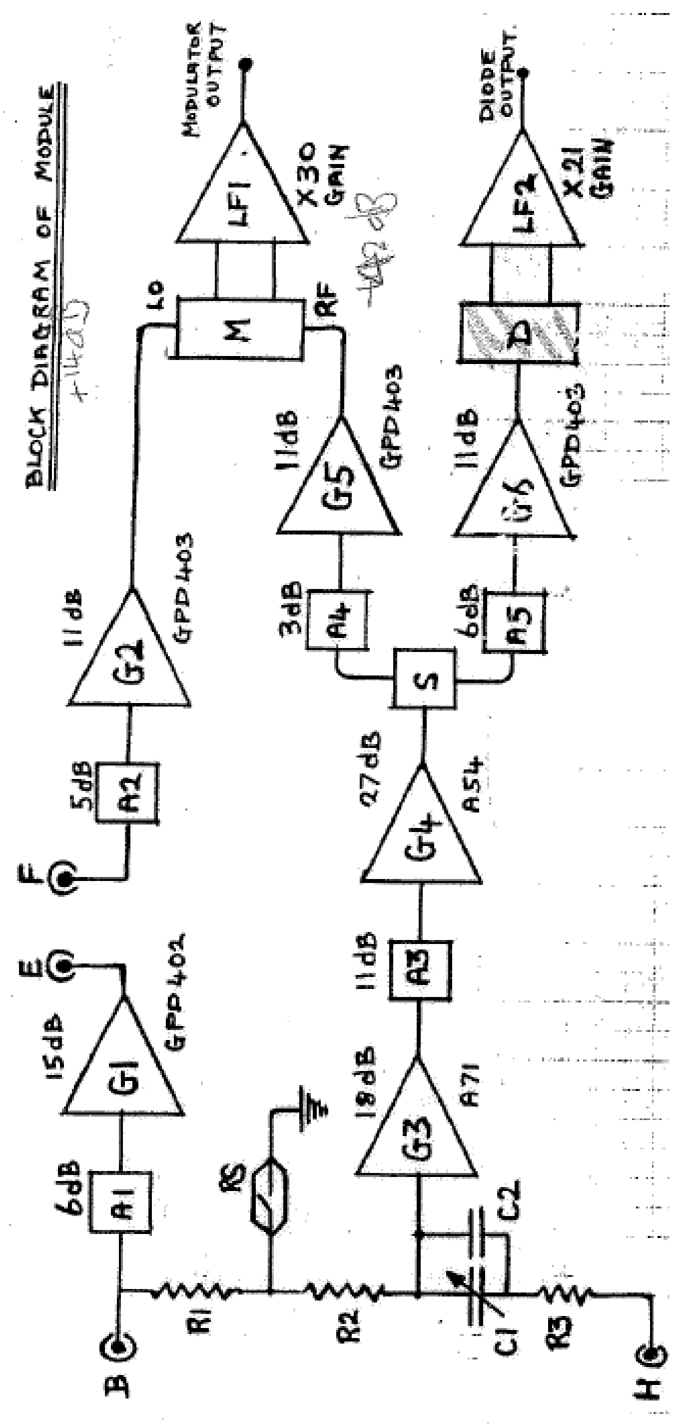


Figure 8: Q meter circuit. G1-G6 are RF amps, LF1 and LF2 are LF amps, A1-A5 are the attenuators (in some cases they are made up of two attenuators in series), RS M and D are the reed switch modulator and diode respectively. The tuneable capacitor is referenced as C1. Reproduced from [5]

4.5.3 Tunable Capacitor

For our purposes we will be restricting our discussion to protons. The nuclear magnetic resonance frequency of protons is 213 MHz. The tuning capacitor introduces a variable capacitance to the circuit allowing for a variable natural frequency of the circuit. The natural frequency of an RLC circuit is

$$\omega_o = \frac{1}{\sqrt{LC}} \tag{33}$$

When a circuit is operating at its natural frequency it acts as an underdamped oscillator, allowing energy to oscillate between the capacitor and inductor. By using the tuning capacitor to tune the Q meter to the NMR frequency of protons, a maximum signal response is achieved.

4.5.4 Full Wave Diode Rectifier

After the signal is sent through a series of op amps and attenuators it is sent to the full wave diode rectifier. The diode converts the signal to a DC output where it can be sent to the post detector stages.

4.5.5 Balanced Ring Modulator

The balanced ring modulator has two inputs, one from the reference signal sent through the phase cable, and the other from the pick-up coils which have traveled through a $\lambda/2$ cable twice. By choosing the length of the $\lambda/2$ cable to be one half the wavelength of the 213 MHz signal, the signal will have traveled through one complete cycle at resonance before reaching the modulator. The modulator compares the phase of the reference signal and the signal from the pick-up coils. If operating at resonance the two signals will be in phase and a maximum DC voltage will be output by the modulator. Off resonance the signals will be out of phase and the DC voltage will be dependent upon the phase difference. If the signals are 90 degrees out of phase, there will be a minimum DC voltage output from the modulator.

4.5.6 Post Detector Stage

For our setup we hope to utilize a Yale Card. The Yale Card acts as a summing amplifier, combining the modulator and the diode signals, to create the resulting signal curve. In addition to summing the signals the Yale Card is able to; control the reed switch, perform the DC convert, and adjust the gain. TTL pulses may be sent from a DIO card to the Yale Card in order to control the features.

4.5.7 Qmeter Housing

A housing was constructed for the Qmeter which would facilitate the connections between the Qmeter and its power supplies, as well as regulate the temperature of the Qmeter. In order to regulate the temperature of the Qmeter, the housing was placed in contact with copper piping which will be used to pump water through. This will rely on conduction to cool the Qmeter during operation. Any deviation from room temperature causes excessive noise to be introduced to the Qmeter's output signal.

Also within the housing are the power supplies. The DB25S connector on the Q meter is solely used to power the internal RF and LF amps and reed relay switch. The necessary power supplies are

- +24V @ 190mA RF amps
- +15V @ 64mA RF amps
- ±15V @15mA LF amps
- +5V @10mA Reed Relay

The connections are as shown in figure 9. The signal diode and modulator signal outputs may be sent to the post detector phases. If the Yale Card is used, connections from the Qmeter to the yale card will be made according to figure 10. The output NMR signal is sent from the Yale Card to ACH3 on the BNC2090 for DAQ. A connection using SMA connectors must be made between E and F on figure 8, this is a delay cable which adjusts the phase of the reference signal and must be modified during tuning.

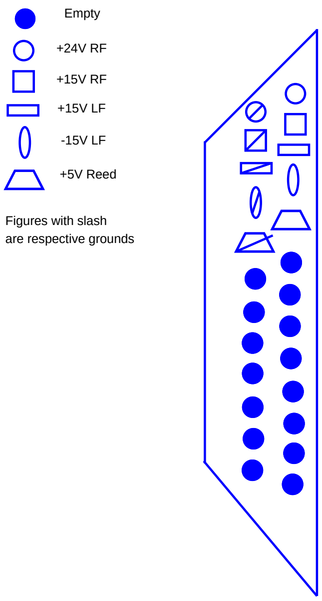


Figure 9: Pin connections on the Qmeter DIN connector

Yale card 32 pin DIN connector

PIN NUMBER		Signals
1		GND (ground)
2		GND
3		GND
4	(grey)	SIGNAL -diode signal IN from Q meter
5		GND
6		SIGNAL-Buffered diode signal OUT
7		GND
8		GND
9	(purple)	Signal-modulator signal IN from Q meter
10		GND
11		GND
12		NC
13		NC
14		NC
15		GND
16		SIGNAL- 1 microsec TTL pulse from Lemo 'CONVERT'
17		common for signals on pins 18 and 19
18		SIGNAL-gain control, gain >1 (set DC level)
19		SIGNAL-gain control , gain > 200 (DC level)
20		Board ground
21		GND
22		GND
23		SIGNAL- NMR SIGNAL OUT
24		GND
25		SIGNAL-DC monitor OUT
26		GND
27		-15V (Blue)
28		-15 V
29		GND
30		GND
31		+15 V (Red)
32		+15 V

Note Pin 17 becomes a Board ground if jumper JP1 is fitted.

Figure 10: Pinout of Yale Card

4.6 Circuit Tuning

The NMR circuit is a RLC circuit and hence resonates at its natural frequency of

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{34}$$

Using a Qmeter to perform NMR measurements dictates that the circuit resonance frequency coincides with the proton resonance frequency of 213 MHz. In order to modify the circuit resonance frequency the Qmeter has a tuneable capacitor. Running PDP in tune NMR mode creates an environment with continuous frequency sweeps through resonance. By putting PDP in tune NMR mode and connecting the reference signal and diode signal to the oscilloscope in X-Y mode it is possible to see the response of the circuit as the RF frequency is swept through resonance. The goal of the tune is to center the roughly parabolic curve with the minimum at resonance. Perform the rough tuning with the tunable capacitor to first acquire a roughly parabolic shape. Once this is achieved, chances are the parabola will be tilted off resonance. If this is the case then it is necessary to adjust the phase cable length using SMA connectors at ports E and F as seen in figure 8. Ideally the parabola will be symmetric about the resonance frequency.

A simple test may be performed to see if resonance has been achieved at the resonant frequency. Begin by moving a crystal oscillator, which oscillates at the resonant frequency and has coils soldered onto the leads, within range of the pickup coil. Because the RF frequency is also the resonant frequency the oscillator will oscillate. When this happens it completes the circuit between the two leads creating an inductor which modifies the inductance of the NMR circuit. If the circuit has been tuned correctly a sharp spike will appear at the center of the parabola, representing a large phase difference between the RF signal and the output of the NMR circuit Qmeter. The spike will occur because with the added inductance the natural frequency of the circuit will shift moving the whole circuit away from the NMR frequency.

5 Results

Throughout the course of this project, strides were made on the software as well as the hardware. LabView 2009 was used to integrate code originally written by Paul McKee. The code included a suite of VI's which are interconnected using TCP and controlled through the *PDP.vi*. The code was originally written using the traditional DAQ drivers from National Instruments. Traditional DAQ drivers are only compatible with Microsoft operating systems prior to VISTA. In order to resolve this problem either the code could be rewritten to incorporate the current DAQmx drivers or the computer could be modified to run an older OS. After beginning to rewrite the code with DAQmx it became apparent that many changes would have to be made, something that would be time consuming. Instead the PC was partitioned to run windows XP.

Additionally, further changes would have to be made to the code regarding paths and addresses. Because the code communicates using TCP, the static IP address from the lab machine needed to be used in all instances which required it. This included the address file as well as path strings at the bottom layer of code.

Finally, paths needed to be changed to fit the local machine. These include the base path, setup file path, as well as all global paths.

In order to interface the software to the hardware, connections had to be made between the GPIB port on the PC to the function generator as well as from the PCI-MIO card to the BNC 2090 breakout. This allowed the LabView software to communicate with and FM the function generator. The BNC 2090 was also used for DAQ. Jumpers were placed on the BNC 2090 to allow for internal triggering so that the DAQ was timed correctly.

In order to incorporate the Qmeter into the NMR circuit, a housing had to be constructed. The housing was responsible for supplying power to the Qmeter and for maintaining thermal equilibrium. To maintain thermal equilibrium, copper plumbing was wrapped in a coil and screwed to the bottom of the housing. Water may be pumped through rubber hosing to the copper piping, which through conduction will regulate the temperature of the Qmeter.

Within the housing are the power supplies. Wall power is run to the housing which distributes it to the power supplies. The power supplies are connected to the DB25S connector on the Qmeter, and are used to power the amps within the Qmeter. Each power supply has an individual ground, running to the Qmeter. The housing also facilitates connections between the function generator and the Qmeter as well as the pick-up coil and the Qmeter.

The Qmeter was successfully powered and is producing a signal. After supplying a reference signal there is a distinct change in the output signal from the modulator. The resulting signal is reminiscent of the output wave forms of the type sra-1 modulator shown in figure 2 of reference [5]. It was also noted that after running the Qmeter for approximately 1.5 hours, noise in the output signal was significantly increased. I am unsure if this is due too drift from thermal equilibrium (there was no water cooling taking place) or an increase in the DC offset.

Also of note is the 5 V pin on the Qmeter. This pin is supposed to control the reed switch so that the Qmeter may be grounded if there are multiple channels. The signal output from the Qmeter is independent of whether 5 V are supplied to the pin or not. It is my understanding that removing 5 V should ground the Q meter and no signal should be produced. This is not the case.

In summary, the PC was configured to allow for control of the NMR functions, including frequency sweeps and DAQ. Data has been successfully acquired into the PDP and analyzed to give a measurement of polarization. The Qmeter has been introduced into the NMR circuit.

Before the Qmeter will be ready to take accurate measurements, a $\frac{\lambda}{2}$ cable must be created and connected to the pick-up coils. The Qmeter must then be tuned to operate at a resonant frequency of 213 MHz. When those two tasks are completed the NMR circuit will be fully functional. Additional duties to be performed include incorporating the PCI-DIO card into the PC, and building a switch box to connect the DIO card to the Qmeters. This will allow for switching between Qmeters. It may be convenient to incorporate post Qmeter signal amplification into the circuit.

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A How-to Run Control Software on New Machine

This is a step-by-step guide to getting the target control software working on a new machine.

- Install an operating system older than Vista (preferably XP)
- Install LabView version of choice
- Install Traditional NI-DAQ (Legacy) Drivers
- Create directory for NMR program
- Create ⋆_Setup_File.txt (where ⋆ is a name of your preference)
- Within ⋆_Setup_File.txt, update the paths (event file and base file) to correspond to local machine and update the channel file
- Create ⋆_Addresses.txt
- Within Create ⋆_Addresses.txt, replace all IPs with machines static IP, or the IP of the machine you wish to use to control the specified function
- Open TPS Global.vi and modify the base path and setup file paths to correspond to local machine
- Navigate to TPS System Start.vi block diagram and modify the string to become ⋆_Setup_File.txt and the filepath to become ⋆_Addresses.txt