A Guide for the EPR Measurement at Jefferson Lab

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1 Introduction

EPR measurement is the alternative way to measure the polarization of the polarized $^3\vec{He}$ target. It can be used either as a direct measurement which provides on-line monitoring of the polarization of the target, or as a means of calibration for NMR measurement, in addition to the calibration done with the water.

2 Electron Paramagnetic Resonance (EPR) Measurement

EPR polarimetry measures the frequency shift of the Rb Zeeman resonance caused by polarized $^3\vec{He}$. Two effects contributed to this frequency shift: The Rb-^{3}He spin exchange interaction which is also responsible for polarization transfer to ^{3}He and the classical magnetic field produced by ^{3}He magnetization. The frequency shift due to polarized ^{3}He is quite substantial and measurable. Since the absolute frequency of Rb Zeeman resonance is determined by both the holding field and the polarization of ^{3}He, by reversing the direction of the ^{3}He polarization, one can measure the frequency difference between the two polarization states, which is proportional to the ^{3}He polarization [1].

Figure 1 shows the overview of the polarized ^{3}He target setup. EPR shares with NMR in the usage of the RF field during AFP sweep, but in a different way. The unique parts for EPR are the photodiode, the EPR RF coil, which are placed above the oven and perpendicular to the main holding field, and a fluxgate magnetometer sensor which is placed within the helmholtz coil but below the AFP RF coil, see section 4 for more details.

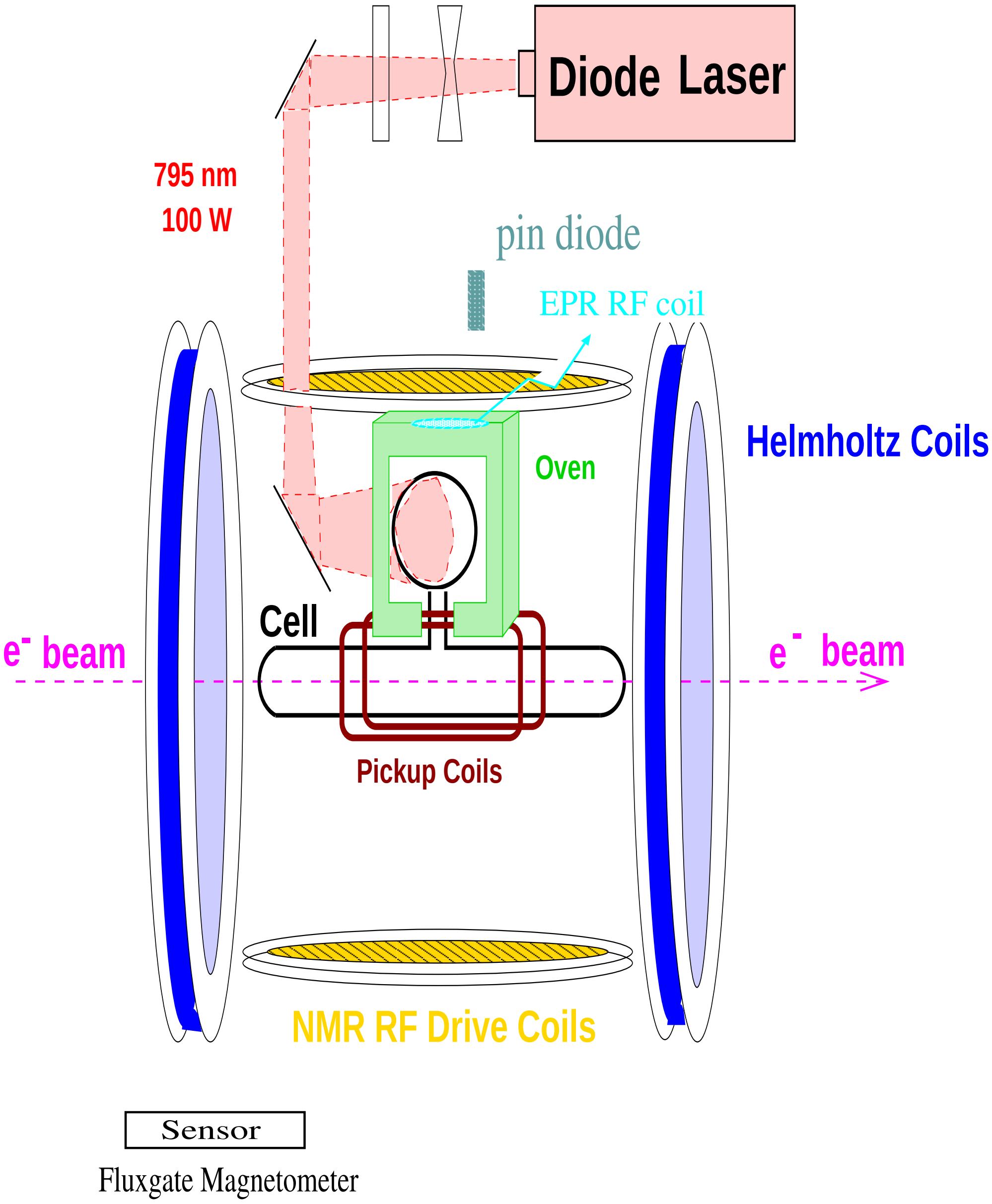

Figure 1: Overview of the polarized ^{3}He target.

2.1 EPR Resonance

To detect the EPR resonance, we relied on the fact that during optical pumping the polarization of Rb vapor is very high (60-90%). It measn that most of the atoms are in the $F = 3, M = 3$ state (or $M = -3$ state for oppositely polarized light). Although the Rb vapor is optically thick for unpolarized light, the laser light can penetrate quite far into the cell because most atoms are in the state that cannot absorb circularly polarized photons from the lasers. Among the atoms that do absorb the photons and are excited to the P state most are radiationlessly quenched to the ground state by the Nitrogen in the cell. A small fraction (3-5%) decays by emitting a fluorescence photon at either D_1 or D_2 line. The fluorescence photons are observed through a D_2filter to block the radiation scattered from the lasers, which are tuned to the D_1transition. These photons form the picture that is usually observed with a photodiode to monitor the optical pumping. The intensity of the fluorescence is proportional to the rate of photon absorbtion in the cell. If we apply an RF field at the EPR frequency corresponding to $M = 3 \rightarrow 2$ transition, it will tend to equalize the population of the two states. The number of atoms in the $M = 2$ state capable of absorbing laser light will increase and thus, the intensity of the fluorescence will increase. So by monitoring the intensity of the fluorescence as a function of the RF frequency we can detect the EPR resonance.

2.2 EPR Lineshape

EPR lineshape measurement provides information on where and what we are measuring. Big noise signal or other resonance nearby may cause confusion sometimes, especially for non-expert. The lineshape measurement is a good way to check whether we are measuring the right signal and it is also a more effective way to find the resonance, especially at the beginning of the measurement. This does not mean that one can get rid of any manual frequency scanning, as described in AFP procedure, at least not with the current setup.

There are two types of lineshape measurement: The Amplitude Modulation (AM) measures the lineshape, i.e. the intensity of the fluoresence changes as function of the EPR RF frequency, while the Frequncy Modulation (FM) measures the derivative of the lineshape as function of the EPR RF frequency.

Amplitude Modulation (AM)

Amplitude Modulation can be used to measure the lineshape of the Zeeman resonances. One can either scan the EPR RF frequency, or scan the main field and convert it back to corresponding EPR frequency. To limit the background contribution, the RF signal sent to EPR coil is modulated in amplitude by a modulation source with frequency f_{mod}. The setup for AM measurement is shown in Figure 2.

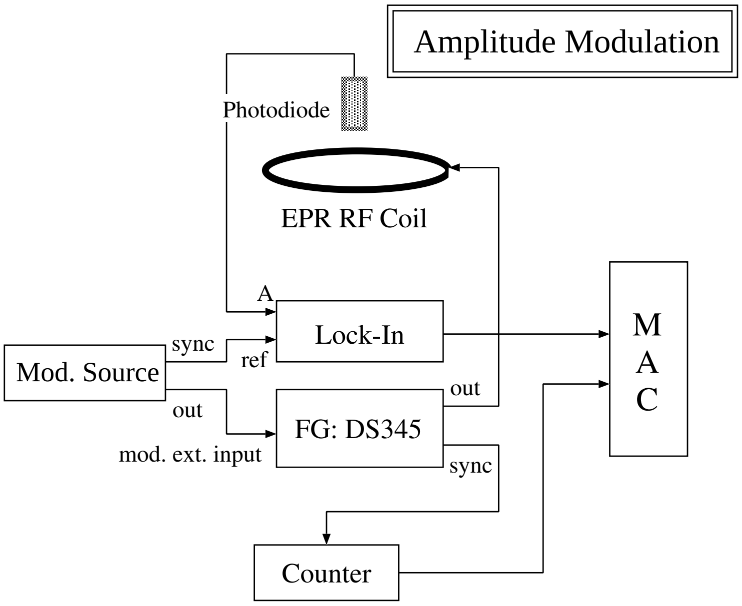

Figure 2: Diagram for lineshape measurement with Amplitude Modulation.

It's easy to understand the principle of AM if one consider the following simplified case: DS345 Function Generator (FG) produces a RF field through the EPR coil with the frequency of f_D: $B_{EPR} = B \cdot sin(2\pi f_D t + \varphi_1)$. Here, φ_1 is an arbitrary phase factor. When $f_D = \nu_{EPR}$, where ν_{EPR} is the resonance EPR frequency, this EPR field is going to induce the transition between the splitted Zeeman states (e.g. M=3->2 for ^{85}Rb). This, in turn, enhances the optical pumping and the fluorescence photon emitted from pumping state. The intensity of the fluorescence detected by the photodiode is thus function of f_D: $I = I(f_D) + I_0$. Here I_0 represents all background signals other than the one induced by our EPR RF field.

The amplitude of DS345 output V_D is modulated with an external source (Mod. Source) of frequency f_m: $V_D = a * sin(2\pi f_m t + \varphi_2) + b$. Here φ_2 is another phase factor, and a, b are twp constants. Since $B \propto V_D$ with some delays which will reflect in the change of the phase φ_3, the amplitude of the EPR field has the form of $B \propto a * sin(2\pi f_m t + \varphi_3) + b$. The change of the RF field strength corresponds to the total energy change, which will show up in the intensity of the fluroescence signal measured with photodiode. If we assume the intensity measured now has the form of

$$I_s = I(f_D) * [a \cdot sin(2\pi f_m t + \varphi_2) + b] + I_0,$$

the Lock-In amplifier will only pick up the component with the frequency corresponding to the one of the reference signal $sin(2\pi f_m t + \varphi_0)$:

$$\overline{x} \propto \frac{\int_0^{\Delta t} [I_s \cdot sin(2\pi f_m t + \varphi_0)]_{hf-filter}\, dt}{\Delta t}$$

here Δt is the Lock-in time constant, which we normally set to $10ms$, $\overline{x}$ is the average output x of Lock-in over time period of Δt, and $hf - filter$ stands for high-frequency filter.

The integration part can be expanded as

$$\begin{aligned} I_s \cdot sin(2\pi f_m t + \varphi_0) &= I(f_D) \cdot a \cdot sin(2\pi f_m t + \varphi_2) \cdot sin(2\pi f_m t + \varphi_0) \\ &\quad + [I(f_D) \cdot b + I_0] \cdot sin(2\pi f_m t + \varphi_0) \\ &= \tfrac{a \cdot I(f_D)}{2} [cos(\varphi_2 - \varphi_0) - cos(4\pi f_m t + \varphi_2 + \varphi_0)] \\ &\quad + [I(f_D) \cdot b + I_0] \cdot sin(2\pi f_m t + \varphi_0) \\ &= \tfrac{a \cdot I(f_D)}{2} cos(\varphi_2 - \varphi_0) \qquad with\ hf - filter \end{aligned}$$

with the filter, only the non-time related term remaines, i.e.

$$\overline{x} \propto a \cdot I(f_D)/2.$$

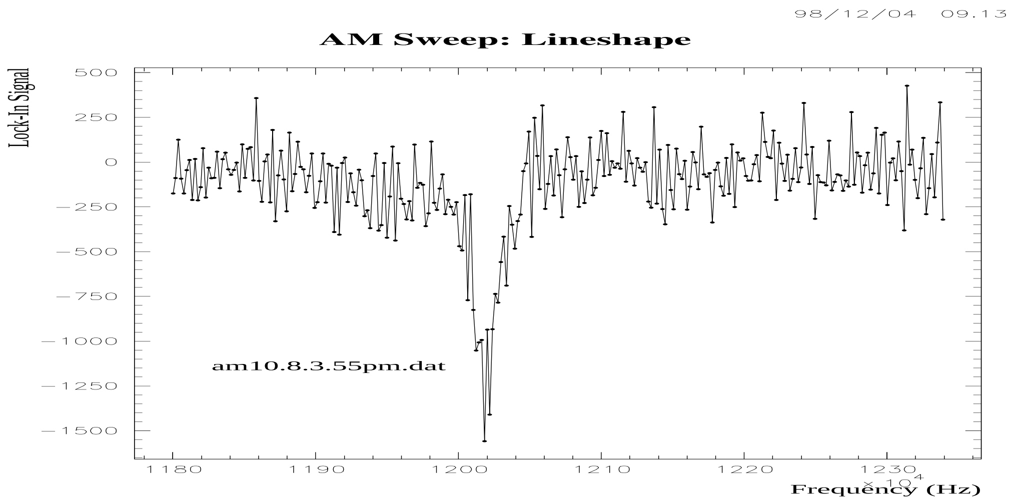

Figure 3: Example of the EPR resonance lineshape taken during expt. E94-010.

By scanning f_D, the Lock-In amplifier will give the output corresponding to the lineshape $I(f_D)$. The data are recorded in MacIntosh (MAC) computer. Figure 3 shows the example of the lineshape measured during E94-010 experiment.

Frequency Modulation (FM)

The frequency Modulation, on the other hand, modulates the RF frequency sent to EPR coil, keep the amplitude of the RF field to be constant. This way, it measures the derivative of the lineshape. The principle used in Adiabatic Fast Passage (AFP) spin measurement, see section 2.3, is the same as described here, although the setup is different. The diagram used for our FM measurement is shown in Figure 4.

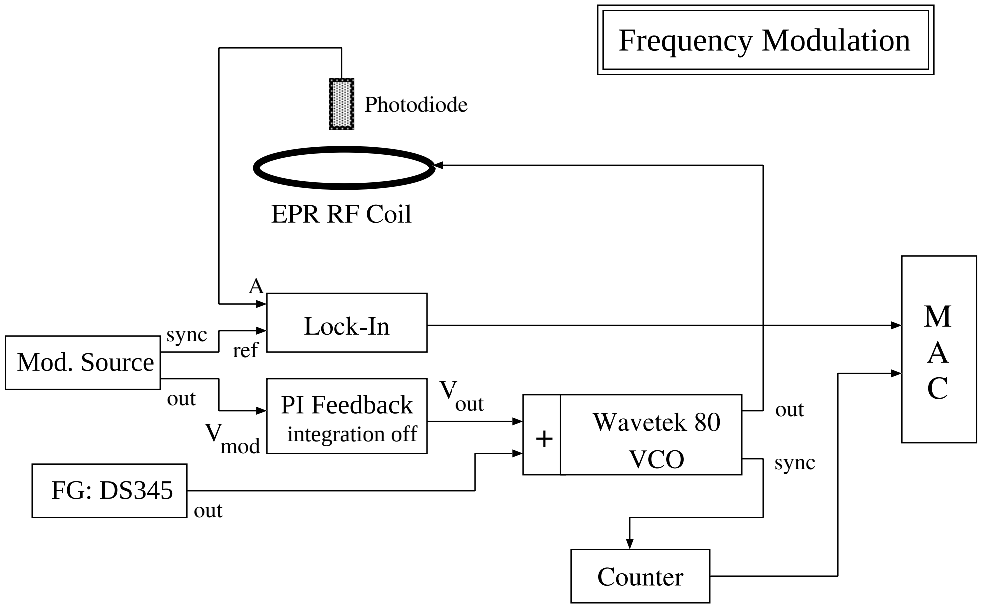

Figure 4: Diagram for derivative lineshape measurement with Frequency Modulation.

Again, to demonstrate the principle, we consider a similar case as in AM:

- Modulation Source output to PI-feedback input: $V_1 = V_{out} = V_m \cdot sin(2\pi f_m t + \varphi_0)$, here V_m and f_m are the modulation voltage amplitude and frequency, respectively, φ_0 is a phase factor;
- DS345 Function Generator provides a linear swept voltage as a function of time: $V_2 = a \cdot t_1$, where a is a sweeping constant;
- VCO input of Function Generator wavetek 80 converts input voltage $V_3 = V_1 + V_2$ into frequency: $f = f_0 + c \cdot V_3$. The output of Wavetek 80 is thus:

$$V = V_0 \cdot sin(2\pi f t + \varphi_2).$$

  Here f_0, c and V_0 are the carrier frequency, conversion coefficient and output voltage amplitude of Wavetek 80, respectively, φ_2 is a phase factor.

The output of wavetek 80 is connected with EPR RF coil and provides the source for EPR RF field. Thus the EPR RF field also oscillates with frequency of f. Similar to the case in AM, when $f = \nu_{EPR}$, the resonance happens. However, unlike in AM, where f is constant at particular time t_1, here f is the function of time t. Rewrite the above equation for f:

$$f = f_0 + \Delta f + c \cdot V_m \cdot sin(2\pi f_m t + \varphi_1)$$

where $\Delta f = c \cdot a \cdot t_1$ and does the scan of the RF frequency.

Since f_m is typically about few hundred Hz, within measurable time Δt (typically $0.5s$), only the average of f is measured:

$$\overline{f} = \frac{\int_0^{\Delta t} f(t)dt}{\Delta t} \sim f_0 + \Delta f$$

The fluorescent photons detected by photodiode I_s is the function of frequency f:

$$I_s = I(f) + I_0$$

assuming all background contributions are in I_0. Following the similar procedure outlined in AM, the Lock-In Amplifier gives output:

$$\overline{x} \propto \frac{\int_0^{\Delta t} [I_s \cdot sin(2\pi f_m t + \varphi_0)]_{hf-filter}\, dt}{\Delta t}$$

Now ignoring the high frequency filter for a moment, since

$$\frac{df}{dt} = c \cdot 2\pi f_m \cdot V_m \cdot cos(2\pi f_m t + \varphi_1),$$

$$\begin{aligned}
\overline{x} &= \tfrac{-1}{\Delta t} \textstyle\int_0^{\Delta t} [I(f) + I_0] \tfrac{d(cos(2\pi f_m t + \varphi_0))}{2\pi f_m} \\
&= \tfrac{-1}{2\pi f_m \Delta t} [I(f) + I_0] \cdot cos(2\pi f_m t + \varphi_0)|_0^{\Delta t} + \textstyle\int_0^{\Delta t} \tfrac{cos(2\pi f_m t + \varphi_0)}{2\pi f_m \Delta t} dI(f) \\
&= \tfrac{1}{2\pi f_m \Delta t} \textstyle\int_0^{\Delta t} cos(2\pi f_m t + \varphi_0) \cdot \tfrac{dI}{df} \cdot \tfrac{df}{dt} dt \\
&= \tfrac{c \cdot V_m}{\Delta t} \cdot (\tfrac{dI}{df}) \cdot \textstyle\int_0^{\Delta t} cos(2\pi f_m t + \varphi_0) \cdot cos(2\pi f_m t + \varphi_1) dt \\
&= \tfrac{c \cdot V_m}{2 \cdot \Delta t} \tfrac{dI}{df} \textstyle\int_0^{\Delta t} [cos(\varphi_0 - \varphi_1) + cos(4\pi f_m t + \varphi_0 + \varphi_1)]\, dt \\
&\propto c \cdot V_m \cdot cos(\varphi_0 - \varphi_1) \cdot \tfrac{dI(f)}{df}
\end{aligned}$$

Note that in above equations, all time t relatied terms vanish due to both the high-frequency filter and the integration over time period Δt.

Since $\frac{dI(f)}{df}$ is the derivative of the lineshape, by measuring the Lock-In Amplifier output as function of EPR frequency, one measures the EPR resonance lineshape derivative. Figure 5 shows an example of the EPR derivative lineshape measurement during E94-010.

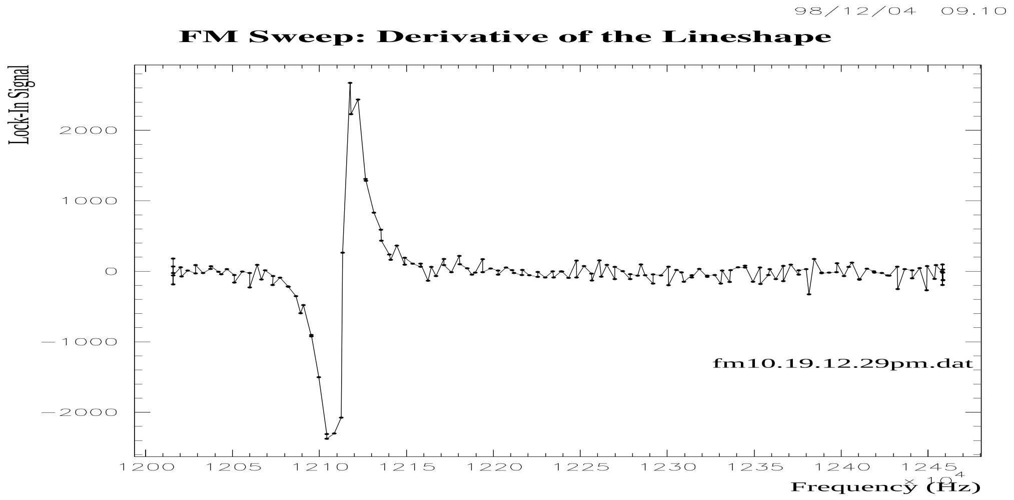

Figure 5: Example of the derivative of the EPR resonance lineshape taken during expt. E94-010.

2.3 Adiabatic Fast Passage Spin Flip (AFP)

The setup for EPR frequency measurement and AFP measurement are shown in Figure 6. The main part of this diagram is similar to the one used in [1]. Since the polarized ^{3}He target used at Hall A, Jefferson Lab uses two sets of Helmholtz coils and the holding field is rotated about 19^0 relative to one set of the coils, we have developed a more complicated scheme to do the field feedback, see section 4 for details.

In Figure 6, the EPR RF field was created by a coil mounted on top of the oven, the fluorescence from the cell was detected by a photodiode with a D2 filter, which blocks the pumping light tuned at D1 line. The EPR RF frequency was modulated using a Voltage Controlled Oscillator (VCO), an input function of Wavetek Function Generator model 80. The signal measured by the Lock-In Amplifier referenced to the modulation frequency was proporttional to the derivative of the EPR lineshape, which principle is already explained in section 2.2.

A feedback circuit was used to adjust the DC level at the input of the VCO to keep the lock-in output signal zero, i.e. locked to the center of the resonance line. The RF frequency was measured by a counter. To accurately determine a shift in the EPR frequency it was important to keep the magnetic field stable to one part in 10^5. We used a Bartington Fluxgate Magnetometer. The field and the field gradient created by the coil near the target were negligible. The coil was driven by a stable current source (stability of 10^{-5} required) that served as a reference to which the field was locked. The output of the magnetometer, which was proportional to the change of the field, was kept zero by a Field Feedback System, see section 4 for details, which controls the

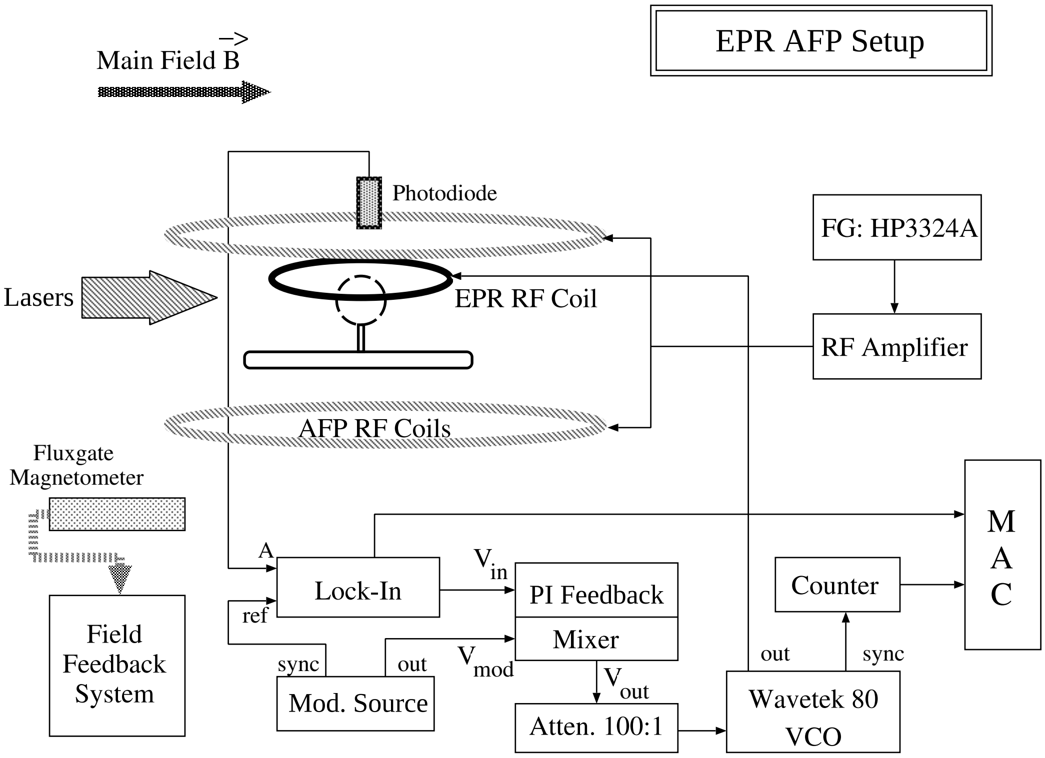

Figure 6: Diagram for electronics setup for EPR AFP and frequency measurement. Detail of the field feed back system see figure 12.

compensation of the change of the power supplies to the Helmholtz coils.

To isolate the frequency shift due to the ^{3}He polarization we periodically reversed the direction of the polarization during the measurement. The reversal was done by Adiabatic Fast Passage (AFP). In stead of sweeping the magnetic field through the resonance line as we did in NMR measurement, we swept the AFP RF frequency. This way we could keep the field locked during the whole measurement cycle. The behavior of the spins during the AFP frequency sweep is identical to AFP field sweep. The end result of the sweep is that the spin of ^{3}He flips 180^o. The equipment used during EPR AFP sweep is the same as the one used in NMR: the AFP coils, RF amplifier, the HP function generator. The function generator was programmed to sweep the frequency at the apporpriate rate to satisfy the AFP conditions:

$$\frac{1}{T_{1r}} \ll \frac{\gamma_{^3He} \cdot \frac{d\omega}{dt}}{H_1} \ll \omega$$

here$\frac{1}{T_{1r}}$, $\gamma_{^3He}$, H_1 and ω are the relaxation rate of ^{3}He in the rotating frame, the gyromagnetic ratio, AFP RF field and its frequency, respectively. This condition is in analogue with the one for AFP NMR sweep where the RF frequency was kept at constant but the main holding field H was swept:

$$\frac{1}{T_{1r}} \ll \frac{\frac{dH}{dt}}{H_1} \ll \omega$$

Table 1: Example of parameters used during EPR frequency measurement.

Parameters	Values
EPR RF Frequency	~12MHz
EPR RF Amplitude	10 Vpp
Modulation Frequency	~200 Hz
Modulation Amplitude	1.6 Vpp
Lock-In Time Constant	10 ms
Lock-In Sensitivity	100 μs
Lock-In Gain	~30 db
AFP RF amplitude	2.4 Vrms
AFP start Frequency	71 kHz
AFP stop Frequency	91 kHz
AFP sweep time	6 s
AFP measuring time	3-10 s
AFP sweeping cycle	2

Typical parameters used during EPR AFP measurement are listed in Table 1: One can choose different measuring time interval during AFP sweep. The general criteria is that it should be long enough to have at least several data points at each spin state, but short enough that it will not cause significant depolarization, since we are pumping in the opposite direction during one of the sweep. This will be a particular concern if masing is present [1].

3 Software for EPR: EPR Master

Most of the equipments used for ^{3}He target control and polarimetries are controlled by power Mac through GPIB connection. Table 2 lists part of the equipments and the GPIB addresses used for NMR and EPR polarimetries. A labview program **EPR Master** has been written for the EPR measurements. Two undergraduate students Mark Jones from Kentucky University and Emma Goldberg from CalTech have contributed greatly towards the development of this program.

Table 2: Summary of the instrument used for EPR and NMR measurement and their GPIB address.

Device Name	GPIB address	Notes
KEPCO power supply 3	3	Main coil 1
KEPCO power supply 4	4	Main coil 2
DS345 Function Generator 1	18	Main field rotation & ramping
DS345 Function Generator 2	20	Main field rotation & ramping
Wavetek 80 FG	17	trigger for ramping
HP3324A FG	19	RF for AFP NMR/EPR
SRS844 Lock-in Amplifier	8	Lock-in for NMR
EG&G Lock-in Amplifier	12	Lock-in for EPR
HP33120A FG	22	Modulation source for EPR
Wavetek 80 FG	23	VCO for EPR
HP53131 Counter	24	for EPR Measurement
DS345 FG	25	for EPR FM/AM
HP34401A Multimeter	26	various
Hall probe	21	meas. main field
FLUKE multimeter	5	meas. main field

3.1 Main Panel

The **EPR Master** has a main control panel shown in Figure 7. It controls three subroutines directly related to EPR mesurements: AFP, FM and AM, and four other general programs which can also be used in EPR related measurement, e.g. measuring

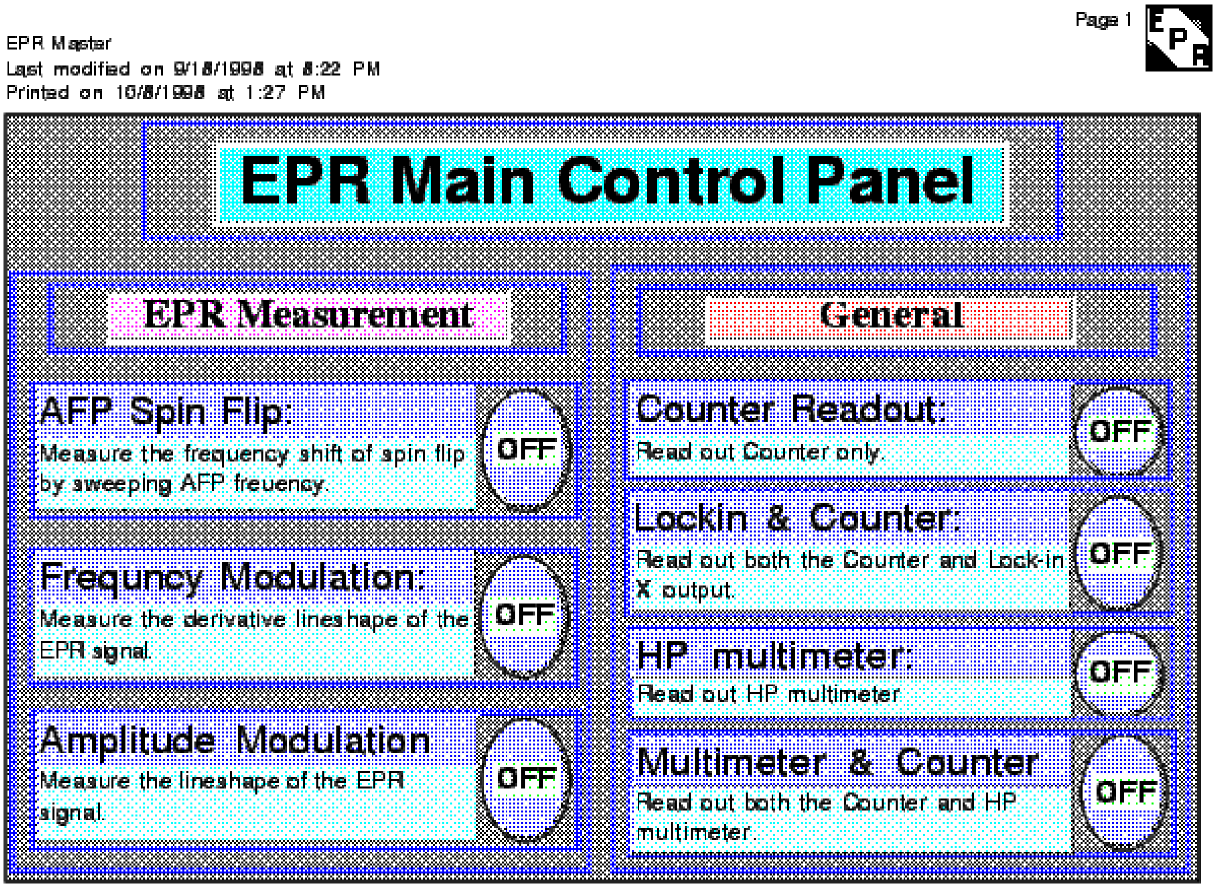

Figure 7: EPR Master main panel

the frequency with Counter Readout, or both Lockin and Counter readout; use HP Multimeter to measure the stability of the power supply etc. Each subroutine has a switch button next to the option which normally marked off. When double clicked on one, the subroutine corresponding to that option will be running, and you will get a new panel open up, as the ones shown in next few subsections. To return to the main panel, click on the button **Return to Main Menu** on the opening subroutine panel for a second or longer.

3.2 AFP

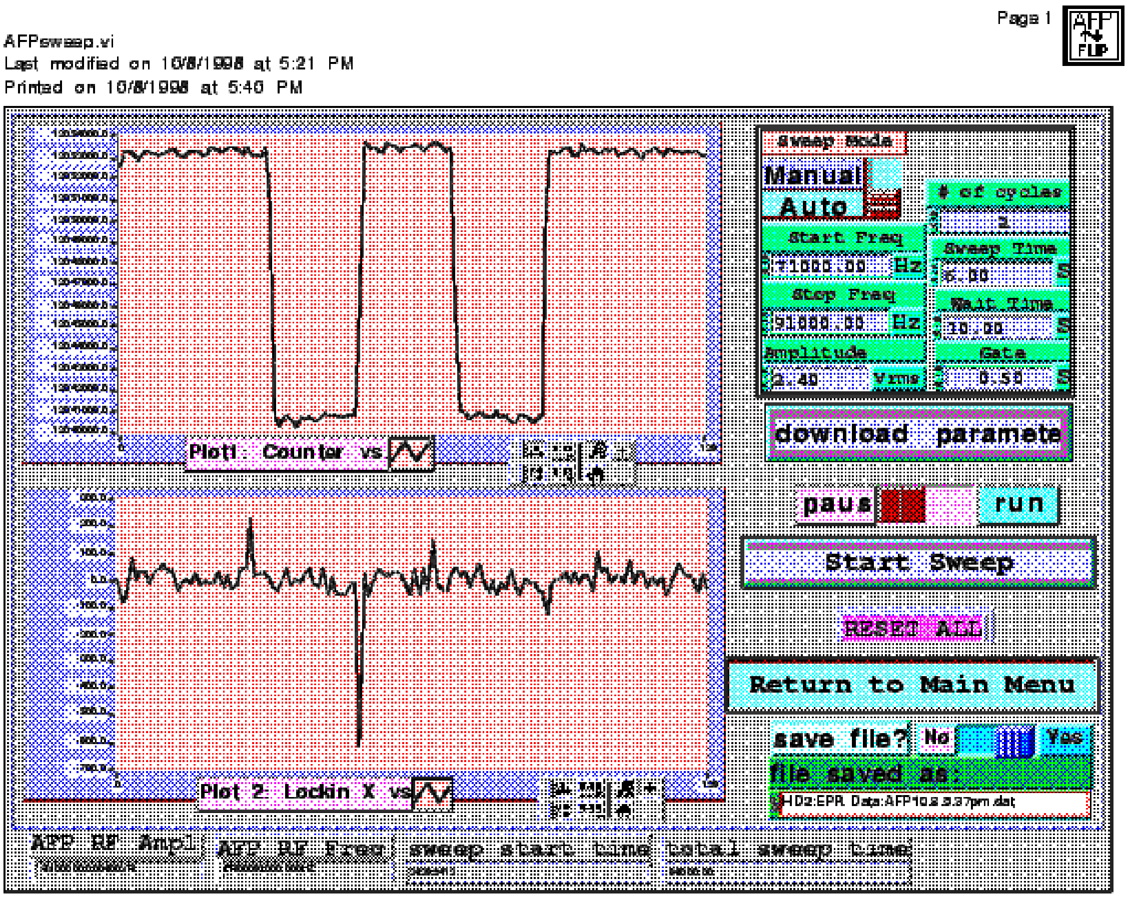

Figure 8: Panel for AFP EPR spin flip measurement.

Figure 8 shows the panel for EPR AFP measurement. There are two sweep modes: "Manual" or "Auto". If "Manual" mode is selected, "# of cycles" in the parameter box will be ignored, and each time when **Start Sweep** button is clicked, it swept once, either up or down, depending on previous sweep. There is potential danger that one may forget how many times you have swept, which may end up in the wrong pumping state. This mode should be only used by expert, or if you REALLY want to change the polarization direction.

"Auto" mode, on the other hand, is designed to sweep in pairs, i.e. always return to initial polarization state. One can specify "# of cycles" to sweep several up and downs. The "Start Freq" and "Stop Freq" are the start (f_1) and stop (f_2) frequencies of HP function generator controlling the sweep of the AFP RF coil. In "Auto" mode, one cycle means the sweep of frequency $f_1 \to f_2 \to f_1$, two cycles means $f_1 \to f_2 \to f_1 \to f_2 \to f_1$ and so on. "Amplitude" is the output voltage amplitude of HP function Generator. "Wait time" is the time interval between two sweeps. "Gate" is the gate time of counter which controls how often to update the measurement. All the parameters in the parameter box will not be updated or down-loaded if the **download parameter** button is not hit. Choose a button position between "pause" and "run" will stop/pause or start the data recording. Normally we start recording data for at least several seconds so we know the frequency corresponding to the initial spin state before we start the sweep by clicking on the button **Start Sweep.** The data will be saved in the file specified in the box below "file saved as".

3.3 FM

Similarly to the case in AFP, the change of the parameters in the parameter box will only be downloaded when the swtich "Update parameters" is clicked towards "Yes". There is message display in the "Status" window which shows the current status of the program. The parameters "start Freq", "Freq range" and "Sweep time" are the ones for the EPR frequency sweep: starting frequency, sweeping frequency range and the time it takes. The "Amplitude" and "Frequency" under "Modulation Source" bar are the parameters for modulation source. "EPR field Ampl" sets the output voltage amplitude to EPR coil. "Gate" is the gate time set for Counter readout. When switch **Sweep Trigger** to "Start", it will start both the sweeping and the data taking, which is displayed in the two upper graph on the left: The Lock-in and Counter vs. time. When the FM sweep finishes, a 2D plot will show up in Lockin vs. Frequency plot on the bottom.

3.4 AM

The panel for AM is very similar to the one for FM. But the circuit is different. The different parameters are: "Start Frequency", "Stop Frequency" of EPR frequency during AM sweep; "Mod. Range" of the amplitude of EPR field (or in another word, EPR coil voltage). Also check the message displayed in the "Status:" window for current status.

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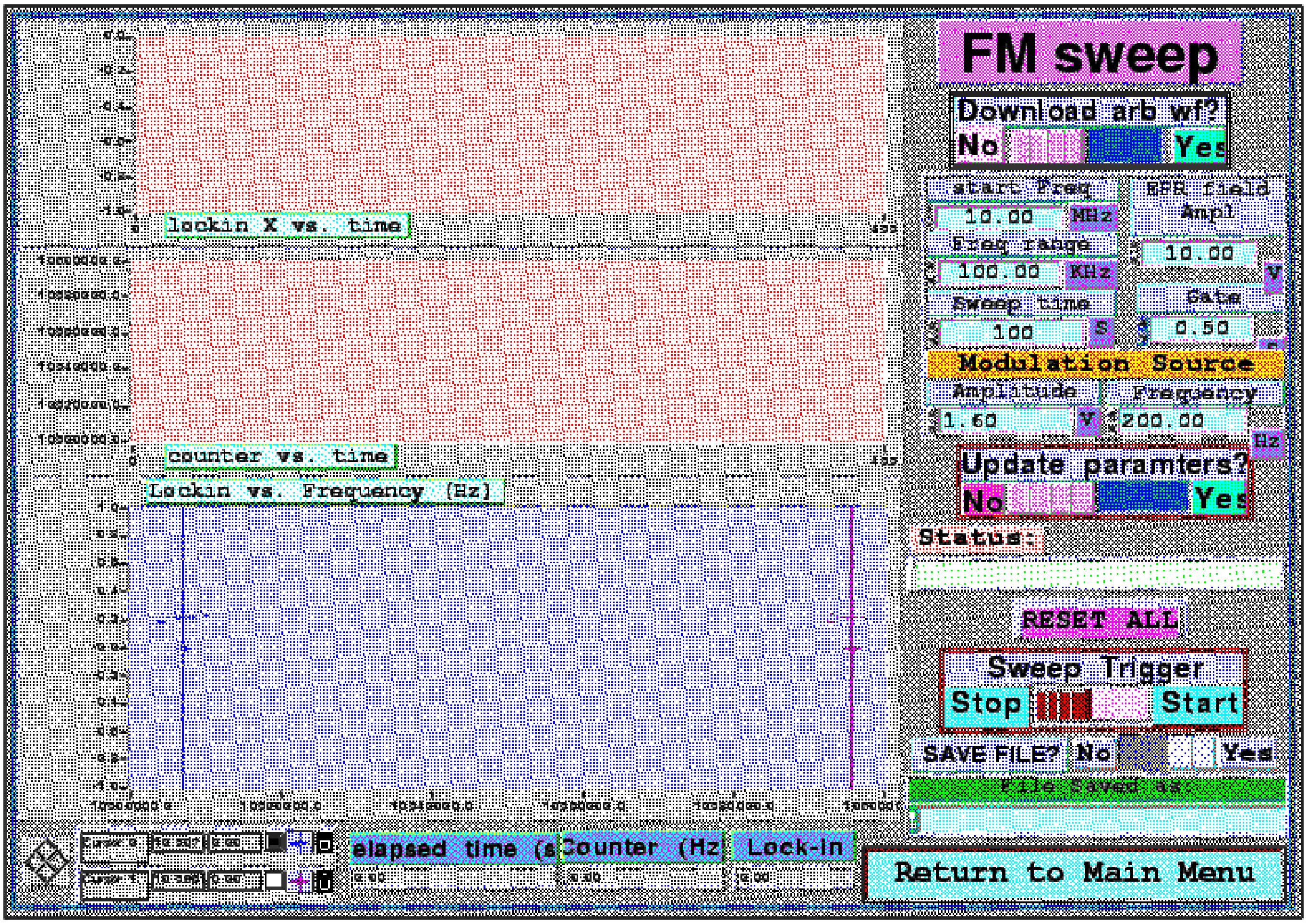

Figure 9: Panel for FM measurement.

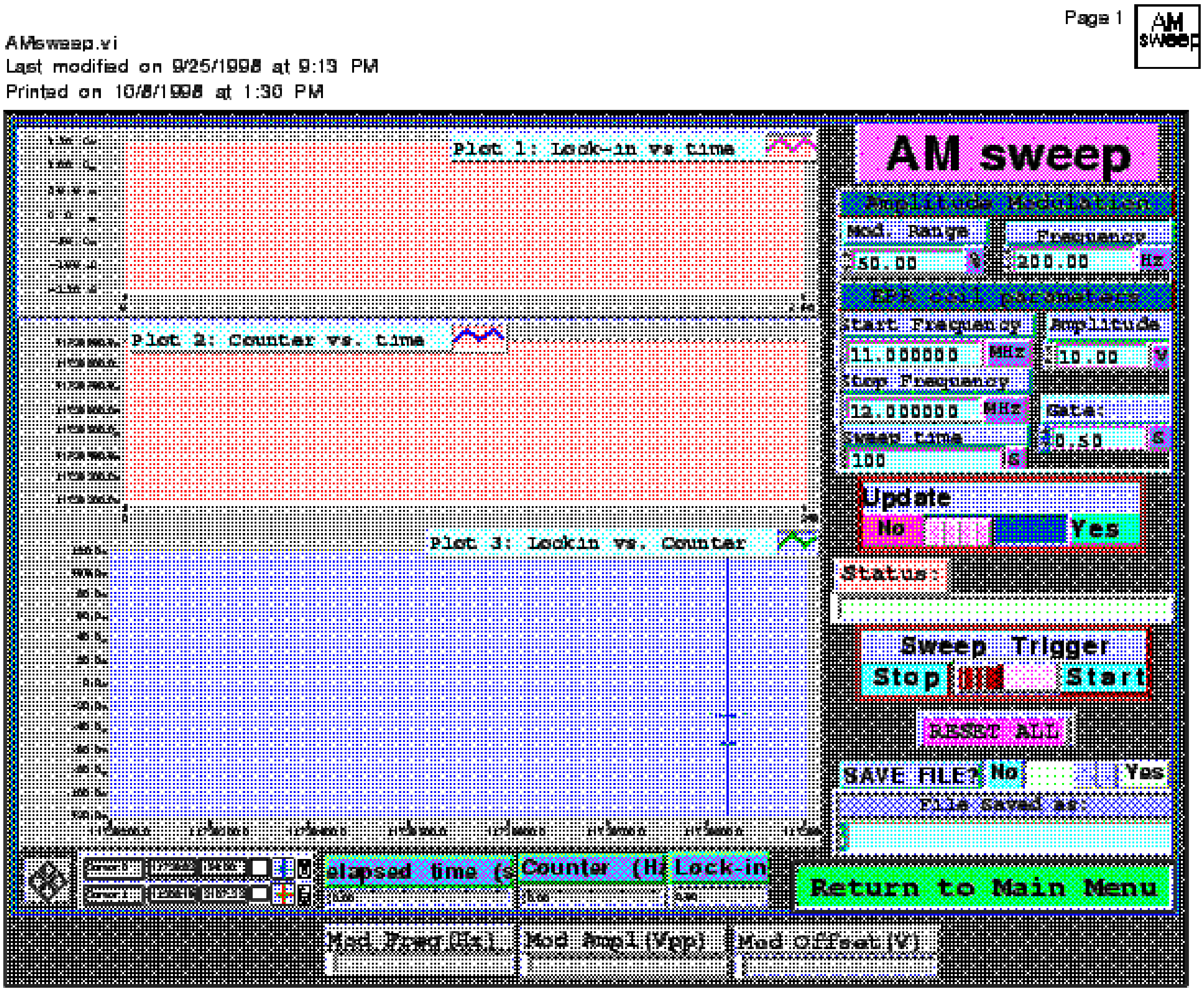

Figure 10: Panel for AM measurement.

3.5 Other Subroutines for Diagnosis

There are four simple subroutines grouped under "General" in the main panel. They are designed for some simple measurement, or diagnosis. They are: Counter, Counter with Lock-in, Multimeter, Multimeter with Lock-in. Only the modules mentioned are under Mac Labview control. The graph in "Counter" and "HP Multimeter" displays the readout of the module as function of time, while the other two also display the Lockin readout in a second graph. For HP Multimeter and Multimeter with Lock-in, one should choose the operation mode in HP Multimeter first: "DC" or "AC"; "Current" or "Voltage". An example of the program is shown in Figure 11.

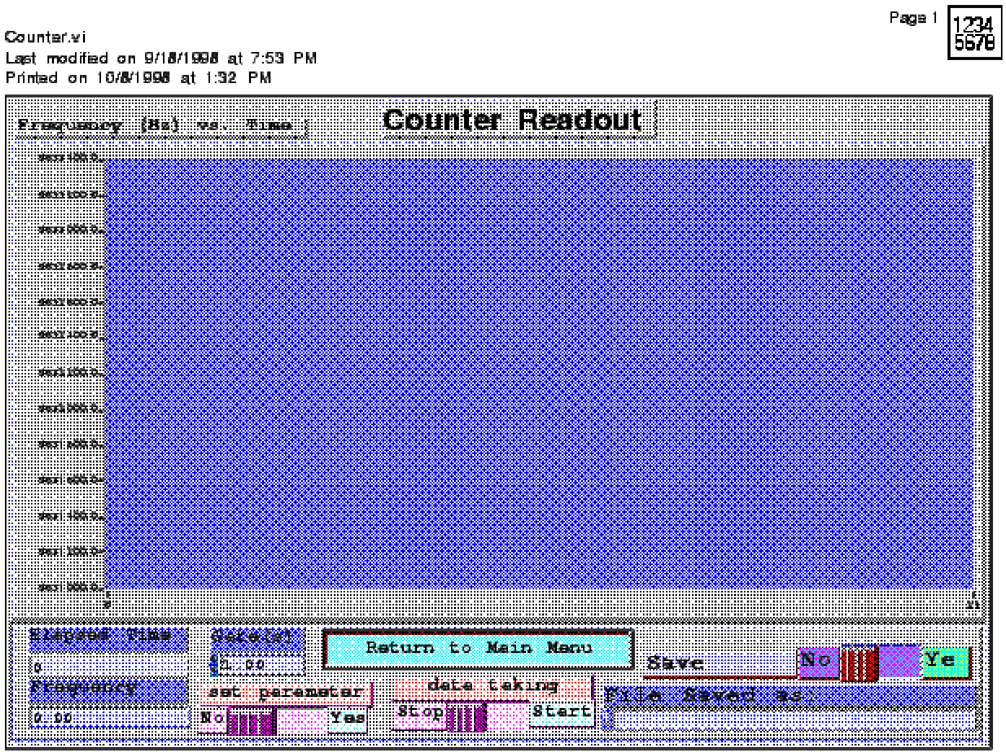

Figure 11: Programes used for EPR frequency measurement.

4 Field Feedback Circuit

The source of the biggest uncertainty in the EPR measurement is the main holding field. Any drift or noise in the field is going to affect the EPR frequency. For AFP measurement, only the short term stability of the field matters, whereas if one wants to monitor the polarization change by measuring the absolute EPR frequency over long time period, the long term stability of the field is required.

4.1 The Principle and Setup

One major difference between the target setup at SLAC and here at Jefferson Lab is the orientation of the holding field. We use two sets of Helmholtz coils with two KEPCO power supplies to rotate the main field about 19^o wrt the axis of one set of the coils, and to rotate the field by 90^o to switch between parallel and transverse pumping modes (wrt the beam line). Because of this, we need to decouple the components of the field change due to the corresponding power supply before we can compensate for this change.

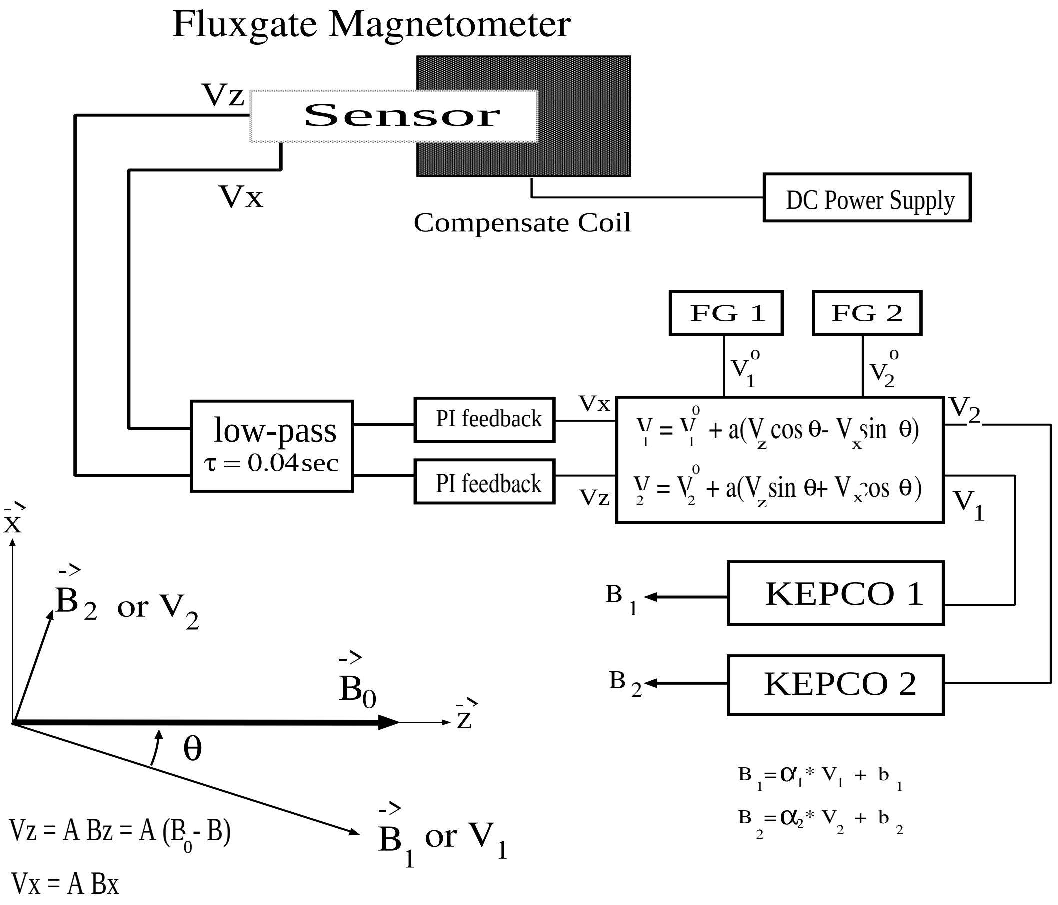

Figure 12: Diagram of the field feedback system.

The schematic diagram of the field feedback system is shown in Figure 12. $\overrightarrow{B_1}$ and $\overrightarrow{B_2}$ are the fields of each set of Helmholtz coils driven by one KEPCO power supply. Each KEPCO power supply itself is controlled by a function generator (FG) with output voltages of V_1^0 and V_2^0 respectively. When there is no feedback, the outputs of the field feedback circuit box V_1 and V_2 are V_1^0 and V_2^0. Assuming the calibration constants are

α_1 and α_2,

$$\begin{aligned} B_1 &= \alpha_1 \cdot V_1^0 \\ B_2 &= \alpha_2 \cdot V_2^0 \end{aligned}$$

the total field at target position is $\overrightarrow{B_0^0}$ and with angle ϑ with respect to one set of the coil:

$$\overrightarrow{B_0^0} = \overrightarrow{B_1} + \overrightarrow{B_2}$$

$$\vartheta = atan(\frac{B_2}{B_1})$$

We use the high precision 3-axes fluxgate magnetometer to monitor the small change in the main field. The sensor is placed within the Helmholtz coil and well below the target cell, so the change in the polarization will not affect the measurement in the change of the main field. The sensor is orientated such that one of the axis is poining along the main field direction, and another is pointing in the horizontal plane. Let's call them V_x and V_z as shown in figure 12. A compensate coil connected with a stable DC power supply is wrapped outside the sensor and provides the reference field $\overrightarrow{B}$. Assuming the conversion constant of the fluxgate magnetometer is A, and the main field at the sensor position is $\overrightarrow{B_0}$, then

$$\begin{aligned} V_x &= A \cdot B_x \\ V_z &= A \cdot B_z = A \cdot (B_0 - B) \end{aligned}$$

If at time t_0 we set $\overrightarrow{B} = \overrightarrow{B_0}$, i.e. $B = B_0$, and we have orientated the sensor such that $B_x = 0$, then the fluxgate magnetometer outputs $V_x = 0$ and $V_z = 0$. At time t, if the field has changed, we will have non-zero outputs V_x and V_z. These two outputs will be used to decouple the changes caused by each power supply and added to the primary control signals V_1^0 and V_2^0 correspondingly:

$$\begin{aligned} V_1 &= V_1^0 + C_1 \cdot (V_z cos\vartheta - V_x sin\vartheta) \\ V_2 &= V_2^0 + C_2 \cdot (V_z sin\vartheta + V_x cos\vartheta) \end{aligned}$$

Here C_1 and C_2 are the scaling constants depending on the sensor position, calibration constants etc. Note that in above equation, depending on the sensor orientation and the coordinates chosen, V_x and V_z are actually $\pm V_x$ and $\pm V_z$. Remember the output of the sensor itself can be positive and negative, depending on which direction the field changes, to be general, we define $V_x, V_z > 0$ corresponding to $B_x, B_z > 0$ and $V_x, V_z < 0$ corresponding to $B_x, B_z < 0$, and

$$\begin{aligned} V_1 &= V_1^0 + C_1 \cdot (s_{11} \cdot V_z cos\vartheta + s_{12} \cdot V_x sin\vartheta) \\ V_2 &= V_2^0 + C_2 \cdot (s_{21} \cdot V_z sin\vartheta + s_{22} \cdot V_x cos\vartheta) \end{aligned}$$

here s_{ij} are either $+1$ or -1, depending on the definition of the coordinates and field direction.

Since we use the positive or negative DC output of the Function Generator to control the orientation of the main field, the field calibration constants α_1 and α_2 also have signs. This has been absorbed into s_{ij}'s so that C_1 and C_2 are both positive numbers:

$$C_i \quad = \quad \left|\frac{B_0^0/B_0}{\alpha_i \cdot A}\right|, \quad i = 1, 2$$

Here, B_0^0 and B_0 are the main fields generated by Helmholtz coil at target and fluxgate magnetometer sensor positions, respectively. Here we have assumed that B_0^0 and B_0 are perfectly parallel. This condition will not be satisfied if the sensor is positioned to close to one Helmhotz coil or positioned outside the coils.

The detail of the field feedback box circuit is shown in figure 13.

4.2 How to adjust field feedback ciucuit parameters

Calibration constants of the main field

The first thing one needs to do, before turn on the feedback circuit is to get the field calibration constants α_1 and α_2 for each set of the coil as defined in section 4.1. The procedure is relatively simple: first connect all the cables and set the field feedback circuit in the "bypass" mode, then set the FG voltage which is the input to the KEPCO power supply and use a Gaussmeter to measure the Helmholtz coil field. One needs to calibrate the coils one set at a time. One should also pay attention that if the coils were cold before the calibration, in which case one may have to wait long enough ($\sim$ 10 hours in our case) to get the field stabilize, especially if KEPCO is operated in the voltage mode.

Set the Helmholtz field to the normal operating field. Using the Gaussmeter to measure the field at target position (B_0^0) and the fluxgate magnetometer sensor position (B_0). Now we can calculate the coefficient C_1 and C_2 according to the formular given in section 4.1. The convension of the field direction and angles are defined in Figure 14. One can use a compass to check the field direction when both sets of coils are in operation.

Setup the fluxgate magnetometer

The fluxgate magnetometer sensor is positioned on a plate with two holders aligned in a line. One of them is wraped with compensate coil outside and stopper inside and towards the end. The other holder is just a plate with a big hole in the middle, and a screw on the top to fix the sensor position. The whole plate is rotatable around vertical axis (let's defined it as y-axis), and there is another screw beneath the plate to enable/disable this rotation.

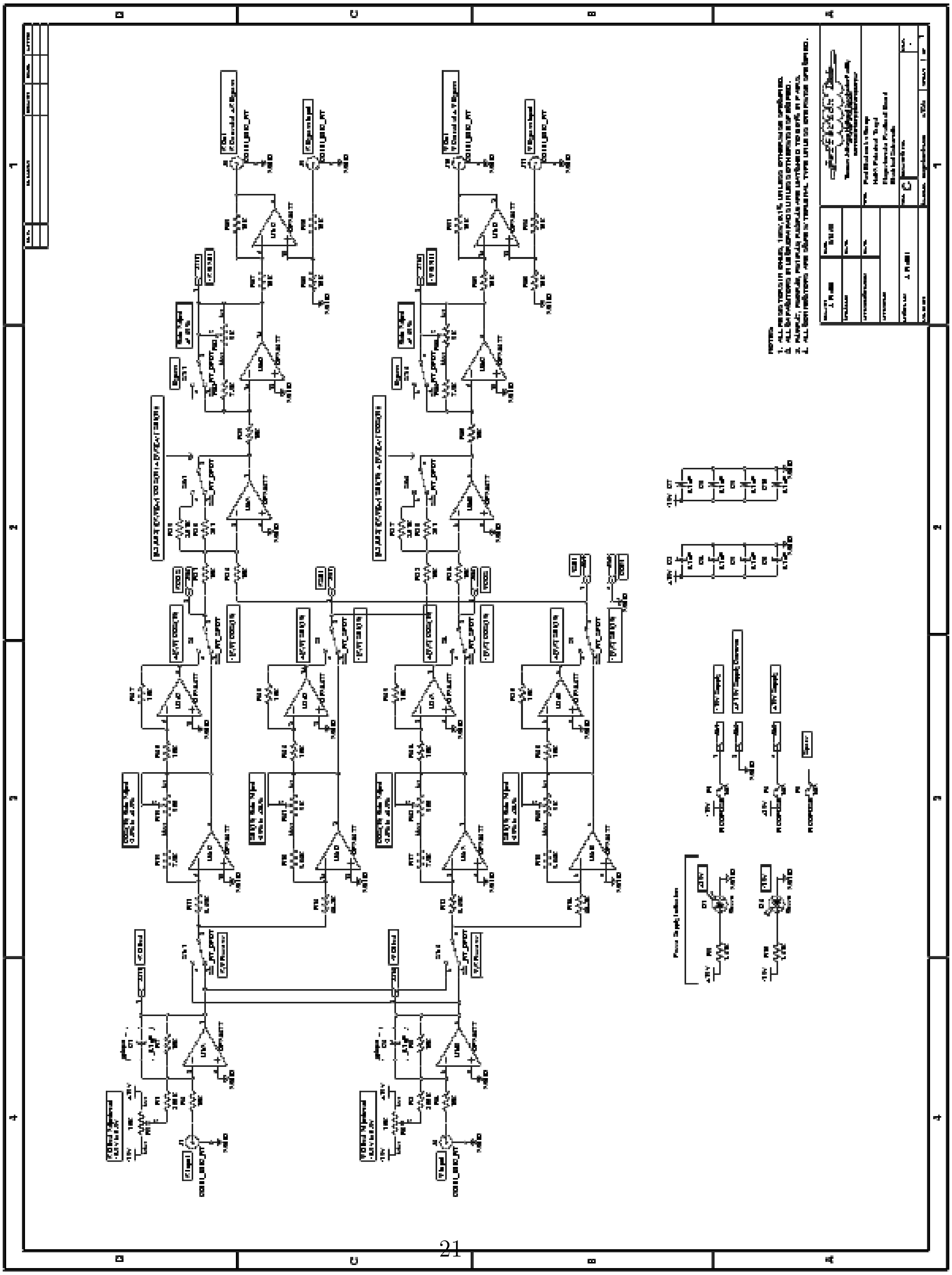

Figure 13: Diagram of field feedback circuit. See [2] for details.

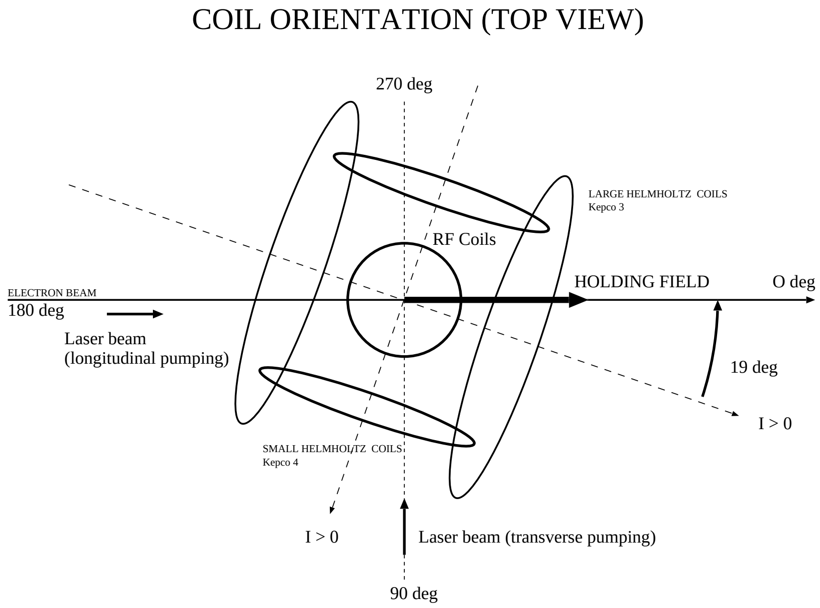

Figure 14: Definition of coordinates and field directions [3].

Before connecting the cable to the fluxgate magnetometer sensor and compensate coil, turn off the power supply to the sensor and the DC power supply. After the connection, set the DC power supply for the compensate coil in current mode and set the current roughly corresponding to the compensate field. This way can minimize the iterations needed. Connect the cable to the sensor, connect the output of the sensor V_x to a scope. Orientate the sensor such that the V_x readout is the minimum. Rotate the plate vertically (around y-axis) first, and then rotate sensor horizontally (around z-axis) to fine tune. The non-zero but minimum output (between +0.5 V and −0.5 V) can be compensated by the "offset" in the Field Feedback System, and be adjusted to zero.

Now connect the V_z output of the sensor to the scope, fine tune the DC power supply for the compensate coil till the V_z readout is also minimum. And check the V_x again, which should still be the minimum, and if it is not, try to rotate a little around its z-axis. Check the V_z again if you changed any setting for V_x.

Procedure of adjusting parameters

There are three sets of parameters to be adjusted: angles, gains and offsets. The first two sets (angle and gain) should be tuned first, leave the offsets to be the last one being adjusted, once every thing has been set up and fine tuned.

There are eight test points and eight adjustable screws on the field feedback box front panel. Since this is a very sensitive and high precision device, we made the screws half hidden, so no accidential touch would cause any change in the settings.

The angles and gains are the parameters based on the best knowledge we have. The angles are for $xcos\Theta$, $xsin\Theta$, $ycos\Theta$, $ysin\Theta$, where Θ is the z-axis of the fluxgate magnetometer sensor relative to the central axis of one of the main coil (large). In this experiment, at longitudinal mode, it's 19^o, whileas at transverse mode, it will be 109^o. To minimize the chance of confusion when rotating the field and reorientate the fluxgate magnetometer sensor along the main field $\overrightarrow{B}$, we will not switch the input signals to the feedback circuit, but instead, will flip one of the switch labelled ($xcos\Theta + ysin\Theta$, $ycos\Theta + xsin\Theta$) to switch the "Xin" and "Yin" inputs.

There is a switch for the gain parameters, which is, in reality, a factor of 10 switch. This is because we have two ranges of fluxgate magnetometer sensor: 1 Gauss and 10 Gauss, and subsequently, this will give different calibration effect to the gain.

There are four input connectors and two output connectors on front panel of the field feedback circuit: X_{input}, Y_{input}, $X_{Bypass-input}$, $Y_{Bypass-input}$ and X_{out}, Y_{out}. The $X_{Bypass-input}$, $Y_{Bypass-input}$ and X_{out}, Y_{out} should already be connected before doing the field calibration: $X_{Bypass-input}$ and $Y_{Bypass-input}$ should be connected to the outputs of two FGs, X_{out} and Y_{out} connected to two KEPCO power supply front panel inputs. Let's assume KEPCO1 (the large coil) corresponds to $X_{Bypass-input}$, which is connected to X_{out}, one should connect the fluxgate magnetometer V_z output to X_{input}. Then V_x output of the fluxgate magnetometer will be connected to Y_{input}.

The recommended procedure to adjust the parameters are:

1. Terminate one of the inputs X_{input} or Y_{input}. let's assume Y_{input} is terminated. Connect X_{input} to a DC source V_{DC}. Set the (*bypass, active*) switch to **bypass**.

2. Measure the offset test points:

   (a) Set ($xcos\Theta + ysin\Theta$, $ycos\Theta + xsin\Theta$) switch (let's call it XY-switch) to $xcos\Theta + ysin\Theta$, measure the test point X_{offset};

   (b) flip the XY-switch and measure the test point Y_{offset};

   (c) flip the XY-switch back.

3. Calculate the expected values for the test points according to the following table, then adjust the screws corresponding to that test point till your measured values agree with the expected ones:
   * signs are for $\vartheta = 19^0$.

4. Reconnect the fluxgate magnetometer outputs to Field Feedback System inputs X_{input} and Y_{input}. Measure the test points X_{offset} and Y_{offset} again. Now they are expected to be zero, so if it is not, adjust the screws labelled X_{offset} and Y_{offset}. Set the sign swtitches according to the above table for $\vartheta = 19^0$ setting.

Table 3: Expected test point values and the screws need to be adjusted.

test point	expected value	adjust screw	XY-switch	sign* switch
Xcos	$X_{offset} \cdot cos\vartheta$	Xcos	$xcos\Theta + ysin\Theta$	+
Xsin	$X_{offset} \cdot sin\vartheta$	Xsin	$xcos\Theta + ysin\Theta$	+
Ycos	$Y_{offset} \cdot cos\vartheta$	Ycos	$ycos\Theta + xsin\Theta$	+
Ysin	$Y_{offset} \cdot sin\vartheta$	Xsin	$ycos\Theta + xsin\Theta$	-
X gain	$Xcos \cdot C_1$	X gain	$xcos\Theta + ysin\Theta$	
Y gain	$Xsin \cdot C_2$	Y gain	$xcos\Theta + ysin\Theta$	

5. To enable the feedback, turn the (*bypass, active*) switch to **active**. One should see very little change (almost non-recognizable) changes in the KEPCO power supply readings.

Cautions need to be taken:

Be careful before connecting the feedback circuit. One should check the difference during connecting the circuit into the main loop at each step. There should be only very little, if at all, change for input and output signal go through the Field Feedback System in "by-pass" mode. It, however, may cause changes in calibration constant of the main field, between with (in by-pass mode) and without the Field Feedback System. This means one should do the calibration of the main field with the feedback box connected and set at "bypass" mode.

5 Operating Procedures

A detailed descriptions of operating procedure for EPR mesurements during experiments E94-010 and E95-001 are given in [4]. You can download the document via web

http://www.jlab.org/˜mliang/epr_instr_short.ps.

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