JLAB PDI Integrated Magnet Measurement System User Guide

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Introduction

The PDI integrated measurement system used at Jefferson Lab is currently used for rotating coil and stretched wire measurement of magnetic fields. At the heart of the measurement system is the MetroLab PDI-5025 Precision Digital Integrator. The PDI performs the integration of the pick-up coil voltage relative to angular and linear preset increments received from motor encoders or timer events.

Components of the measurement system include the:

- PDI Digital Integrator
- Agilent HP34970A DAQ Switch Unit
- nuDrive NI Multiaxis Amplifier
- FW-7344 Stepper/Servo Motor Controller
- Maxon Stepper Motor w/ HEDL 6540 encoder
- Keithley Multiplexing Unit
- GPIB-ENET/100
- PC w/Firewire and Ethernet Connections
- Jlab intergrated measurement software.

This user guide will cover setup, wiring, software, and use of the measurement system. It should be noted that changes will be made to this system to best fit the needs of Jlab magnet measurement. This guide may be updated as the use and scope of the system changes.

The Measurement System

The measurement system assembly has been constructed in two parts. The first part consisted of joining all of the rack-mountable components in the measurement rack and establishing communication between each component and the host computer. During the first stage of development, the rack was located in an office setting away from the measurement stand. This provided a better atmosphere in which to complete the detailed programming, test component wiring, and configure hardware settings. A function generator was used to create a voltage signal in place of a rotating coil. The component rack layout is shown in Figure 1.

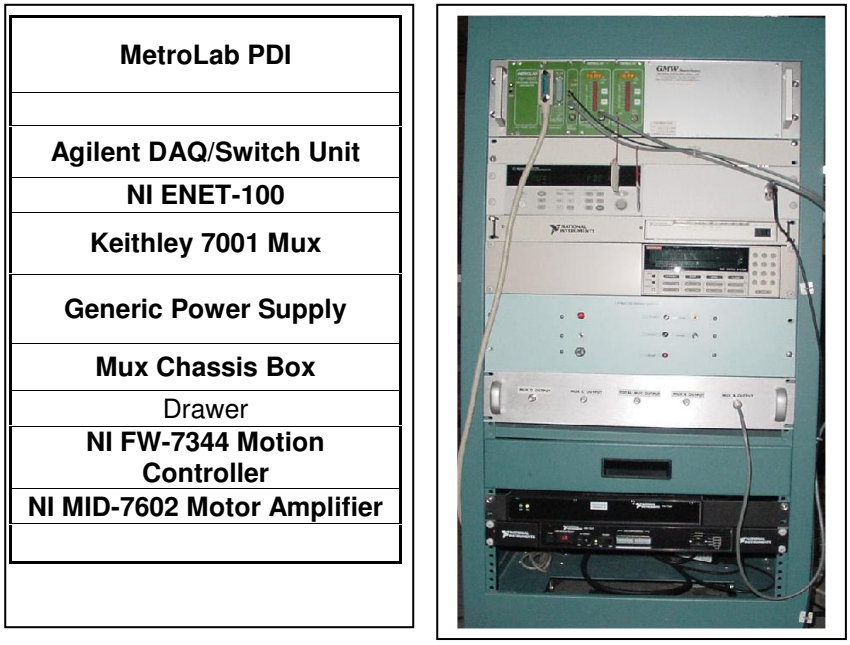

Figure 1 Measurement system rack components

The second part of the measurement system assembly consisted of moving the component rack into the magnet measurement lab, establishing communications with the DAQ computer, and wiring the motor, encoder, and probe to the system. Multi-stand parts were fabricated to quickly switch between the older CAMAC system and the new

PDI system. This was done so that, during commissioning, the existing CAMAC components could be swapped out easily if multipole measurements needed to be completed. The current layout for the measurement stand is shown in Figure 2.

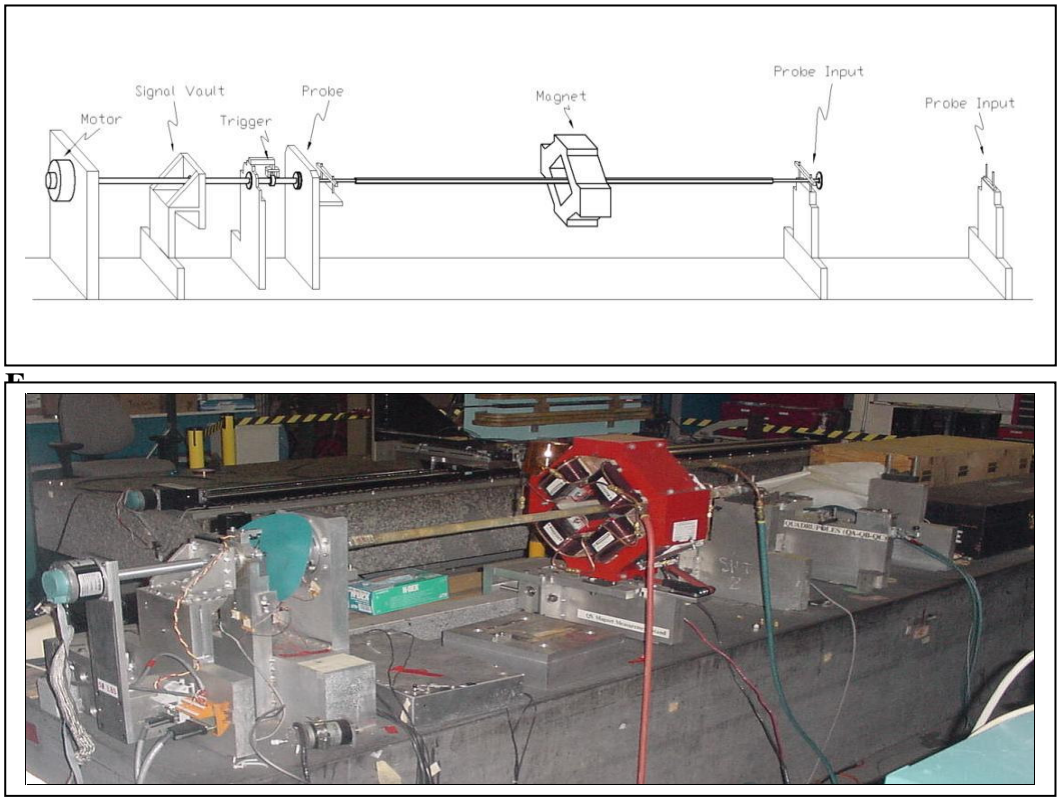

Figure 2 Multipole measurement stand

PDI Data Acquisition Software

The measurement process is controlled by a software program written in C using LabWindows/CVI as the compiler and IDE. SLAC provided control software that is currently used at their facility for their PDI measurement system. This software was used as a foundation from which the JLab measurement system software would be created.

The goal of the software is to create a hybrid of the two existing software models that can be used by a magnet technician with an intermediate skill level to operate the PDI measurement system. Also, there is a desire to create data output that is consistent with the output from the existing CAMAC measurement system software.

The SLAC software was written to be operated by a programmer or magnet engineer with programming ability. Changes to the parameters specific to each magnet measurement must be changed inside the code and the code recompiled prior to the measurement. Interaction with the user is done through a DOS window command line prompt although several informative GUI graphs could be made visible during a measurement by setting code parameters.

After a review of both the SLAC and CAMAC code models the decision was made to make changes directly to the existing SLAC code. Even though several of the components used in the SLAC measurement system are the same as those used at JLab, several components are different and have had new code written for instrumentation control. The initial focus was to implement code for the different hardware used at JLab

and tie it into the SLAC code in place of their similar components. Specific instrumentation controls have been developed for the motion hardware and data acquisition switch unit as well as controls built to handle magnet powering during the measurement.

To decouple the need for a programmer to be involved in setting up the parameters for a magnet measurement, a GUI interface, parameter file, and parameter file editor were developed for the new PDI software. The start up screen for the new PDI software is shown in Figure 3. From this screen the user can select an appropriate parameter file, set specific job information, and initiate a measurement run. Expert control screens for the various component in the system can also be accessed from the start panel for system debugging, creating new parameter files, and general component operations.

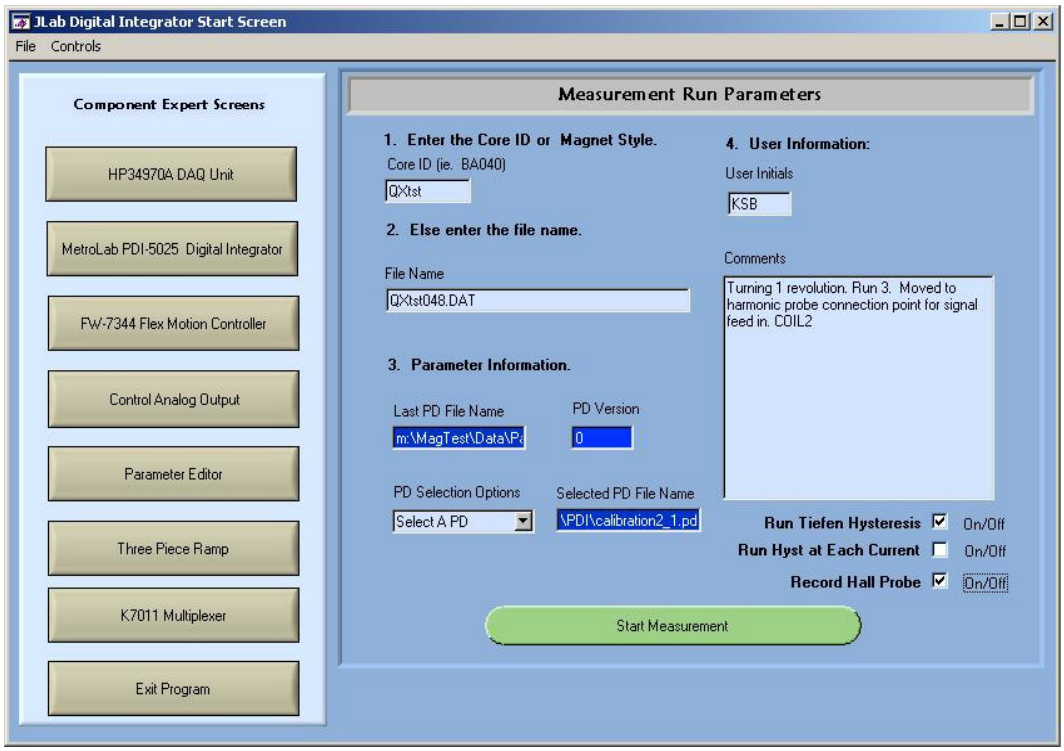

Figure 3: PDI software start screen.

The CAMAC parameter file was used as a template to create the PDI parameter file. The CAMAC parameter file contained some unused information which was excluded from the PDI parameter file in an effort to minimize complexity for the user. Two GUI interfaces were written to create parameter files that would be used to configure the PDI measurement. This parameter file utility panel, shown in Figure 4, is used to configure the typical parameters used for a magnet measurement. It allows the user to build a working parameter file using drop down menu selections. It is especially useful when defining an extensive list of currents settings to be set during the measurement process.

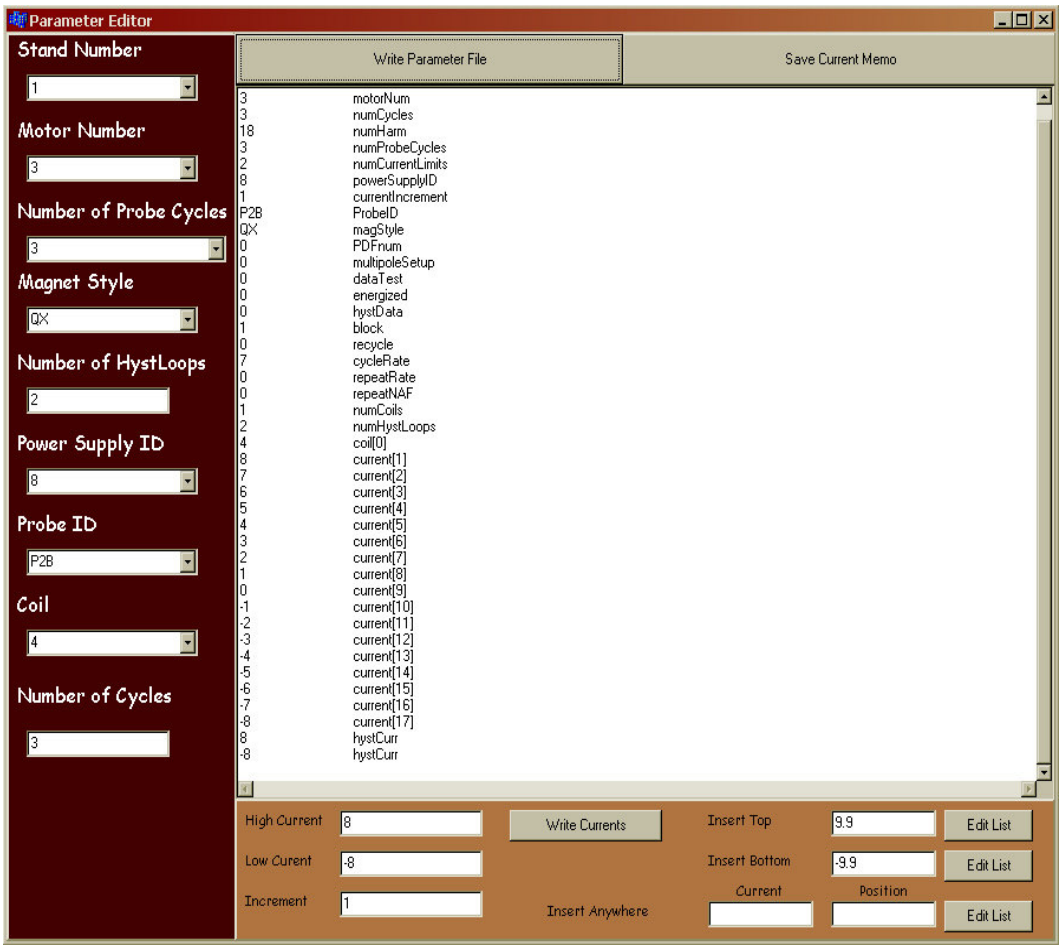

Figure 4 Parameter file creator software panel.

A secondary editor, shown in Figure 5, can be used to make high level changes to the PDI parameter file. In this screen the user can open either an existing PDI parameter file or template and then make changes directly to the file parameters. When this interface is used, the original file is displayed in a bottom window allowing the user to compare the changes that have been made before saving the file. Changes are made directly to the parameter text file. When the new file is saved, the original file is automatically backed up with a decremented extension (*.999).

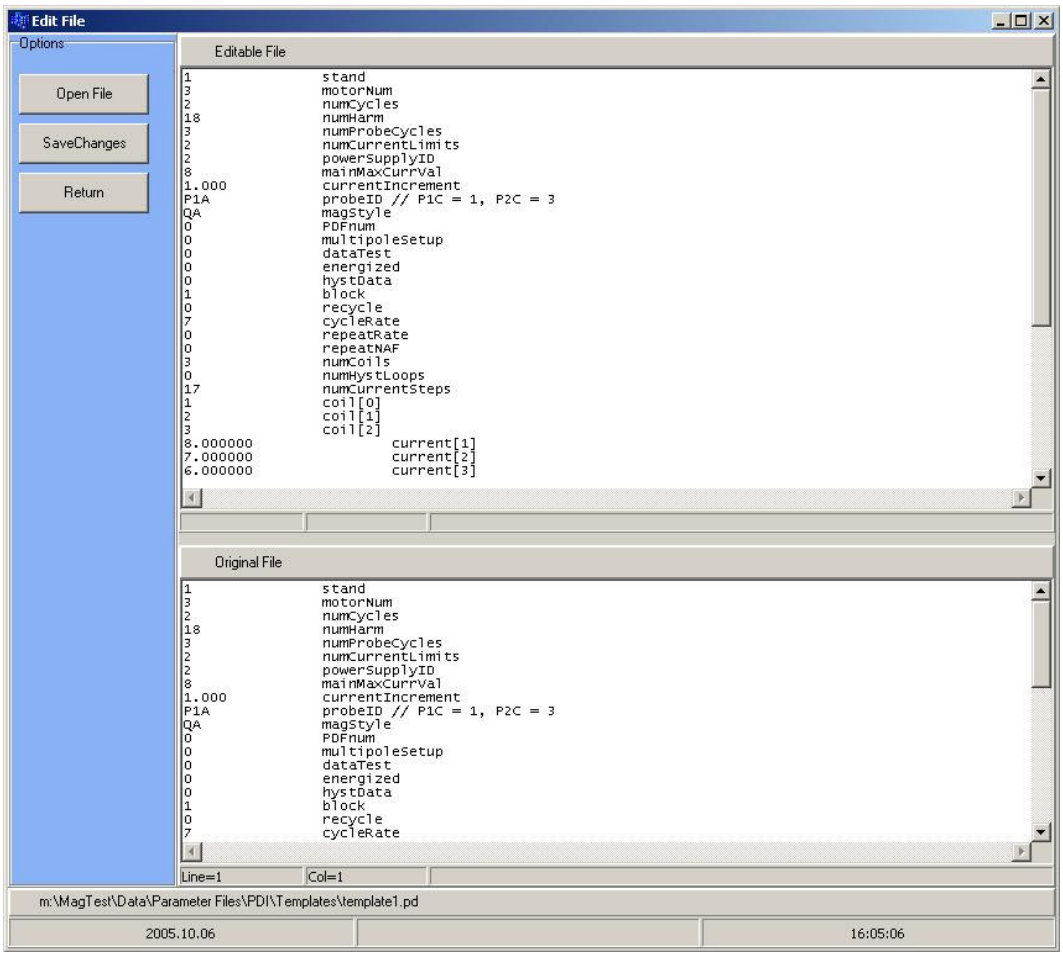

Figure 5 Expert parameter file software panel.

The PDI Runtime Panel, Figure 6, is displayed during a measurement along with two graphing panels developed at SLAC, Figure 7, that plot data relevant to the measurement in an easy to interpret format. The main panel displays the harmonic results from the FFT as well as provides feedback to the operator about the current progress of the measurement and magnet current. The graphing panels display the output from the PDI unit as well as a breakdown of the harmonic strengths from the FFT. The magnet strength, relative to the main harmonic, is also displayed for each measurement current.

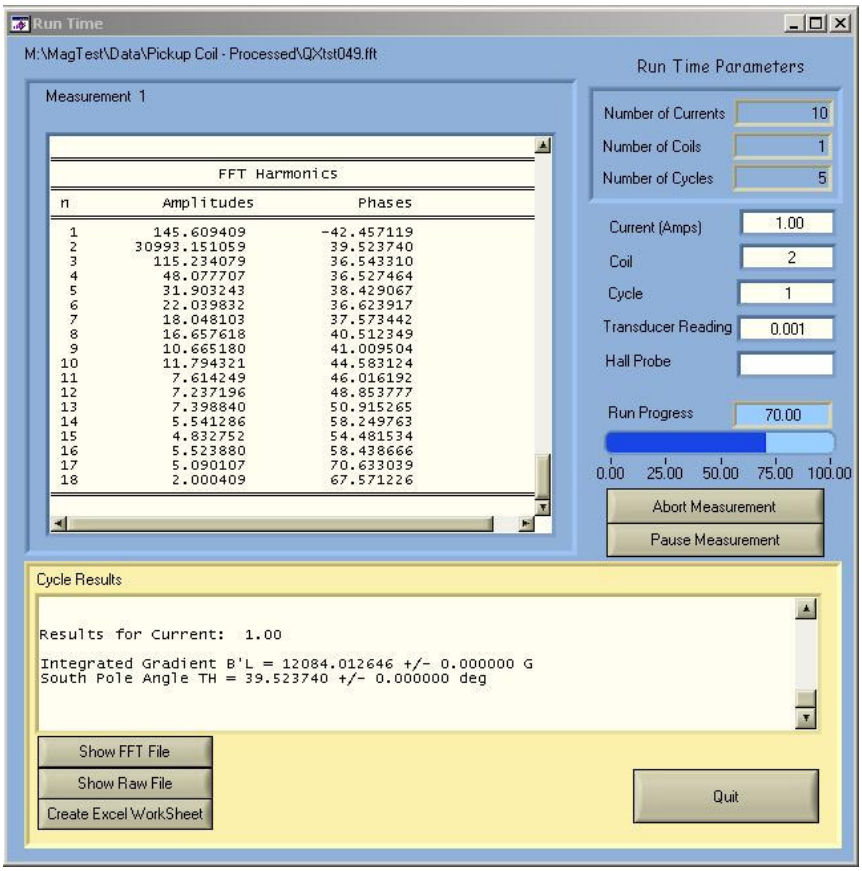

Figure 6 PDI software runtime panel

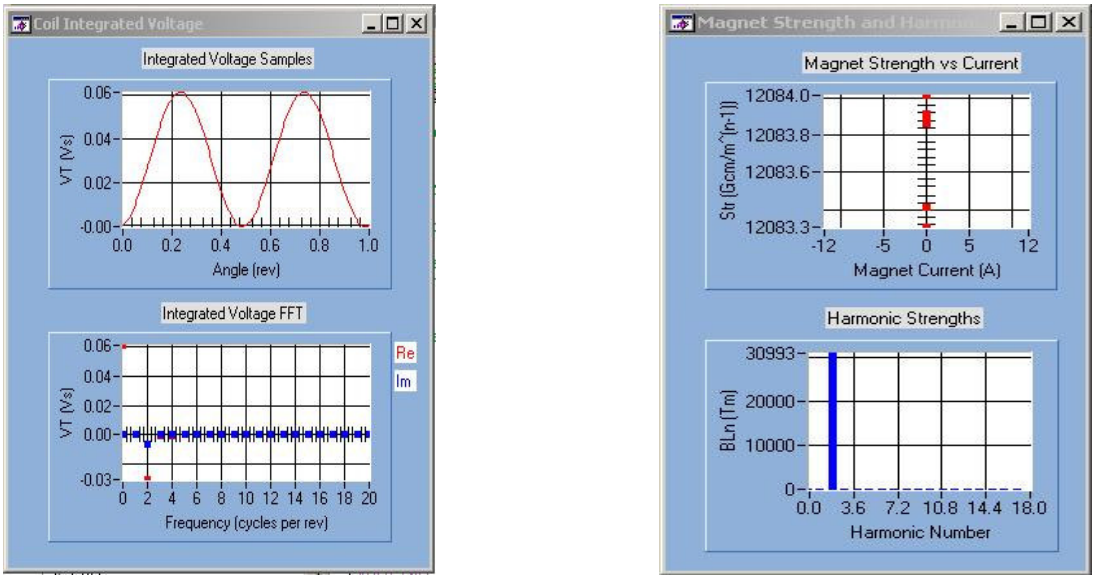

Figure 7 PDI software runtime plots.

Expert Control Panels for the PDI Software

PDI Expert Panel

The PDI expert control panel is used to test and troubleshoot the MetroLab digital integrator. For JLab magnet measurement, encoders are used to integrate the magnet flux based on position. To view the positional information, the PDI encoder counts can be displayed by pressing the "Aquire Counts" button. The "Zero Counter" button is used to reset the PDI encoder count index. High level commands can be entered into the "Send Command" edit box and sent to the PDI to test communications.

Additionally, the "TestRun" button can be used to test a single probe rotation based on time or position. Different types of run testing can be configured by setting specific parameters at the beginning of the "TestRun" function. The PDI Expert Panel is shown in Figure 8.

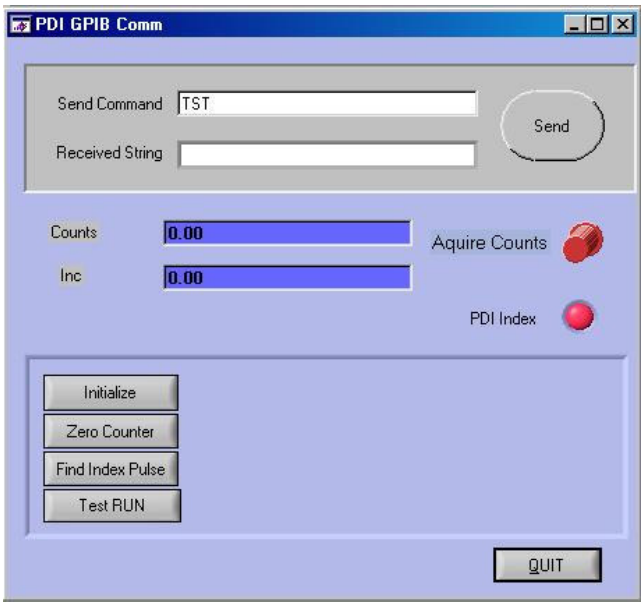

Figure 8 PDI Expert Control Panel

Three Piece Ramp Expert Panel

The Three Piece Ramp expert panel is used to control the FP-AIO analog output control using a defined ramp protocol developed during the PDI commissioning. The analog output from the FP-AIO controller is connected to a Danfysik power supply. The Danfysik reads the input voltage from the FP-AIO controller and sets its output current using 10 V (input) = 20 A (output). From this panel, the user can change ramp speeds, hysteresis limits, and magnet currents.

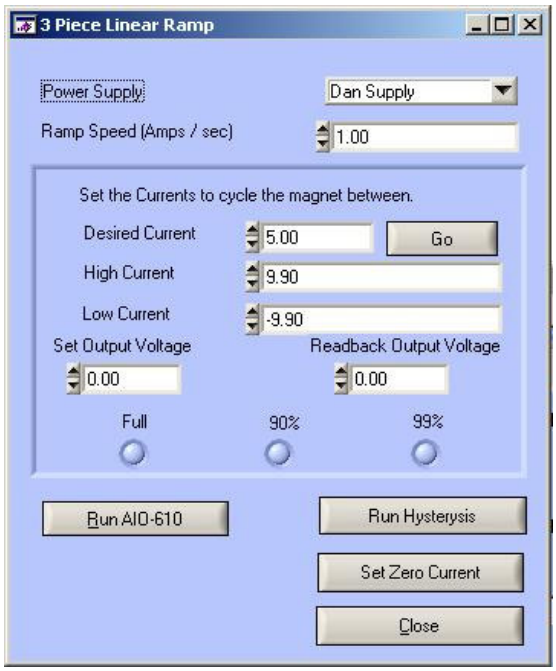

Figure 9 Three Piece Ramp Expert Panel

Keithley MUX Expert Panel

The Keithley multiplexer is used to switch between signals routed from the probes to the integrator. The Keithley User Guide can be found in the MagTest\Documents\Keithley 7001 Mux folder.

Motion Control Expert Panel

The motion control expert panel is used to reset or troubleshoot the measurement stand motor. The panel can be used to send the motor to various positions and cycle the motor between motor increments. When sending the motor to its home position, the motor will rotate towards zero until the home limit switch is activated. At this point, the motor and encoder positions are reset to zero.

A panel button provides an easy means to launch National Instruments Measurement and Automation Explorer software for advanced troubleshooting and configuration control.

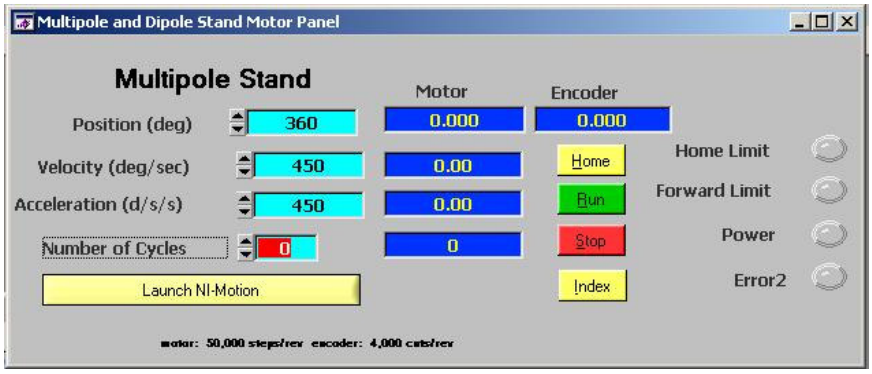

Figure 10 Motion Control Expert Panel

Epics Control Expert Panel

The Epics control panel can be used to control the current supplied to the magnet by the trim rack power supply. The controller issues simple TCP/IP calls to EPICS which independently sets the magnet current or runs hysteresis. A transducer is used in the magnet test lab to verify the current to the magnet is correct.

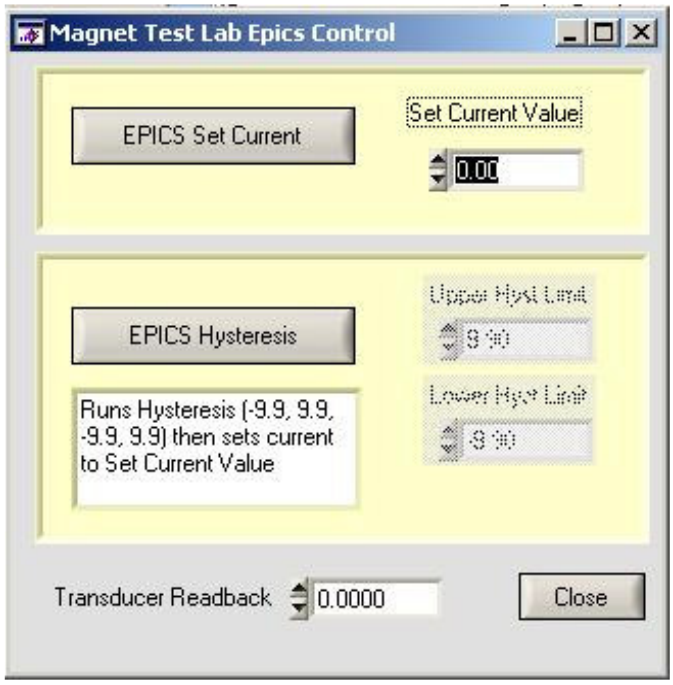

Figure 11 Epics Control

HP 34970A DAQ Expert Panel

The Agilent HP34970A is a multi channel data acquisition unit. The HP34970A control panel is used to read back the 22 channels on the corresponding instrument. Currently, each channel can be configured to readback temperatures using J type thermocouples and 2 wire RTDs, and voltages. The user can select the desired channel configuration from a dropdown menu. The software will then write the configurations command to the instrument when collecting data and save the configuration to an initialization file. The initialization file is read during program start up to load saved channel configurations. The "Start Channel Update" button is used to read all channels sequentially. See the Agilent manual for detailed information.

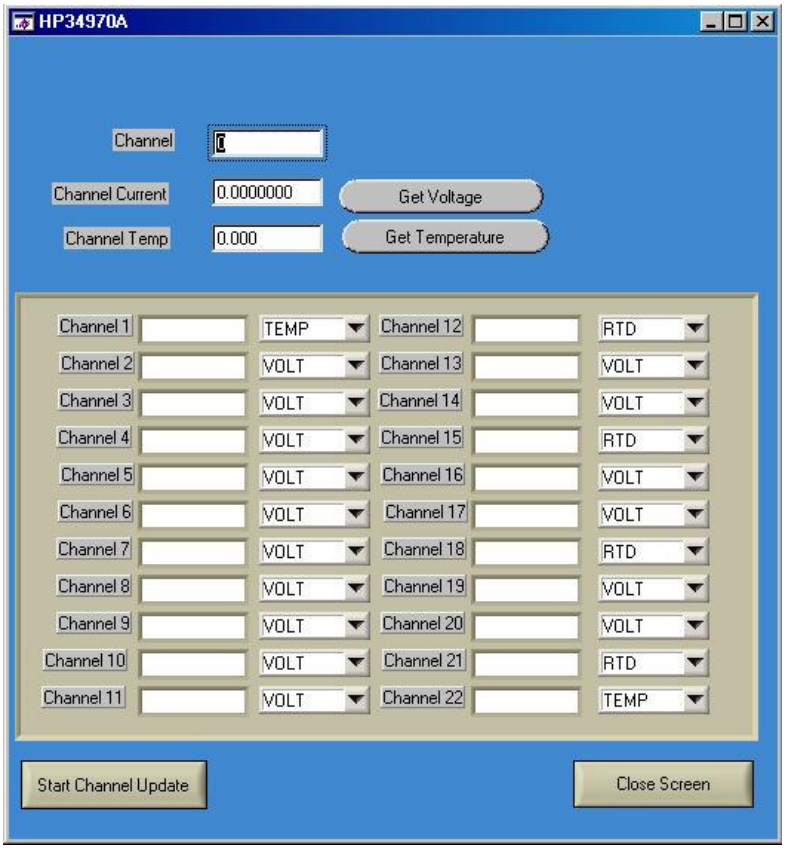

Figure 12 HP-34970A DAQ Switch Unit

Measurement System Assembly Details

Data Transfer and Analysis

Hardware Communication

The National Instruments GPIB-ENET/100 is an Ethernet-to-GPIB controller. GPIB communication is used to control and synchronize the various hardware components in the measurement system. The ENET/100 allows networked computers to communicate with and control IEEE 488 devices from anywhere on an Ethernet-based TCP/IP network. The decision to use the ENET/100 was made to eliminate the need for a PCI-GPIB card to be installed on the host computer as well as enabling wireless control of the measurement system. This will make replacing and upgrading host computers significantly easier.

Host Computer Requirements

A PC using either a Windows2000 or XP operating system is required with an Ethernet network connection for GPIB communication and Firewire cable connection for motion control is required for operation of the measurement system. Appropriate permissions to access the network drive for the magnet test group at JLab are also required to execute the aquisition software version due to the directories the software must access to read and write data during execution and initialization.

Magnet Powering

While different magnets have different powering requirements, the most common quadrupole magnets at JLab are powered using a trim card powering system. In this system, a trim card is used to independently access voltage from a bulk power supply. In this way, multiple trim cards can be attached to the bulk supply and fed to various magnets. The trim card system is controlled by Experimental Physics and Industrial Control System (EPICS), a set of collaboratively developed software tools, libraries, and applications used to create distributed real-time control systems.

Epics

EPICS is used extensively in particle accelerators throughout the world and is the main control system used at JLab. The specific function of EPICS, as it relates to the measurement system, involves the use of its JLab standard protocols to run hysteresis loops and set currents. Because EPICS is run from UNIX based machines through TCP-IP and UDP based communications, a Windows based EPICS Client has been set up on the Windows based Data Acquisition System (DAQ) in the magnet measurement area at JLab. This system has also been tied into the automated DAQ software used for magnet measurement.

Even though this will be a totally different method than that utilized by the magnet measurement group at JLab in the past, EPICS offers distinct advantages over prior test lab based powering methods. First, EPICS is a real time control system capable of operating at a 10Hz resolution. Second, and more importantly, EPICS is the primary means by which all magnets in CEBAF and the FEL are cycled and set. Using the same

current powering control system to map the magnets that will be used to set their current once they are installed in the accelerator or FEL should provide the most realistic field map. By utilizing EPICS, the magnet measurement hysteresis and current setting can match exactly that which is used to power the magnets in the FEL and CEBAF accelerator. Also, the effects of overshoot have been handled in the magnet powering protocol of the EPICS control system. This eliminates the need to quantify differences in the magnet powering techniques used in the magnet test facility versus the FEL.

Three Piece Ramp

To provide a means by which certain magnets can be sent to off-site facilities for supplemental measuring, a secondary powering system utilizing National Instruments FieldPoint Analog Output control is also used. In this case, a separate but standard protocol "a three-piece linear ramp" ensures consistency in ramp rate for a range of power supplies. The first step of the ramp is run at 1 A/s. At 1 A from the set point, the ramp speed is decreased by a factor of 10, and at 0.1 A from the set point the rate is decreased further by a factor of 10. Figure 13 shows the different stages of the three piece ramp protocol when setting a current from 0 to 10 A. Using this method, tests have shown that there is no measurable overshoot of the current at its set point.

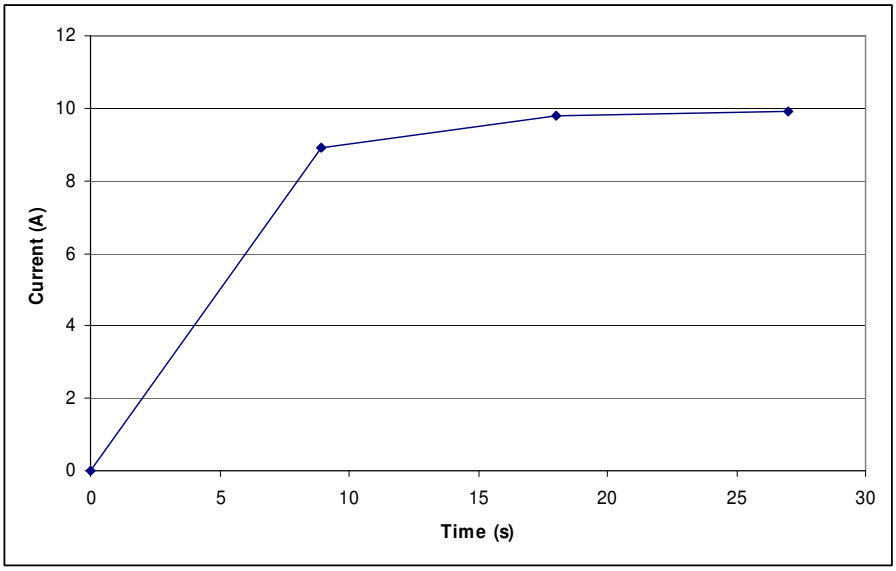

Figure 13 Stages of the three piece ramp protocol used to set magnet current.

At JLab, a Danfysik power supply is used to both mimic EPICS magnet powering protocols and implement custom protocols such as specialized hysteresis and ramp rate algorithm control. Using a +/- 10 volt analog input signal as its control, the Danfysik will output +/- 20 Amps to the magnet. An FP-AIO-610 Ethernet module provides 12 bit resolution and operates between 0V – 10V or -10V - +10V making it ideal for computer automated control. In the event that supplemental magnet measurements are desired from an external measurement facility, a powering algorithm dynamic link library (DLL), a software control, can be written and packaged together with a specific power supply so that it will be accurately powered. This algorithm can then be modeled in either EPICS or on a microcontroller so that once the magnet is installed in the FEL or accelerator, it can be set accurately.

Signal Multiplexing

A Keithley 7001 multiplexer was used to select the input signal for a specific measurement set. The multiplexer has two available slots for signal banks. Each bank is divided into four sections that provide 10:1 multiplexing. One bank is dedicated to the rotating coil multiplexer stand, two other banks are reserved for an existing translating dipole stand, and the fourth is reserved for a stretched wire translational stand. Bucked signals require that the voltage inputs from two coils be routed to a single channel. To do this, the positive sides of the two coils being bucked are routed to a new channel and their associated negative leads are tied together creating a complete circuit. This configuration prevents the bucking process from being done electronically through the Keithley multiplexer. Bucked signals were routed to a new channel in the required configuration prior to the signal being delivered to the multiplexer as a separate input. The assembly chapter also describes an alternative configuration.

Mulitplexer Chassis Box

A chassis box was designed and constructed at JLab to allow the measurement system's input signals to be routed through the Keithley multiplexer and returned to a single output BNC connection. From the chassis output, the signal is then routed to the PDI signal input. The chassis box provides a convenient place in the measurement rack to manipulate the signal wires. The chassis box works in conjunction with the Keithley multiplexer and is able to handle the signals from up to four different measurement stands. The inputs from each stand are routed through twisted pair cable to the chassis box. The cables attach to the chassis through 25 pin D connections. Inside the chassis

box each signal wire is separated and attached to a DIN rail connection point as shown in Figure 14. This provides a convenient place for a computer engineer to troubleshoot signal problems that may be associated with the measurement coils.

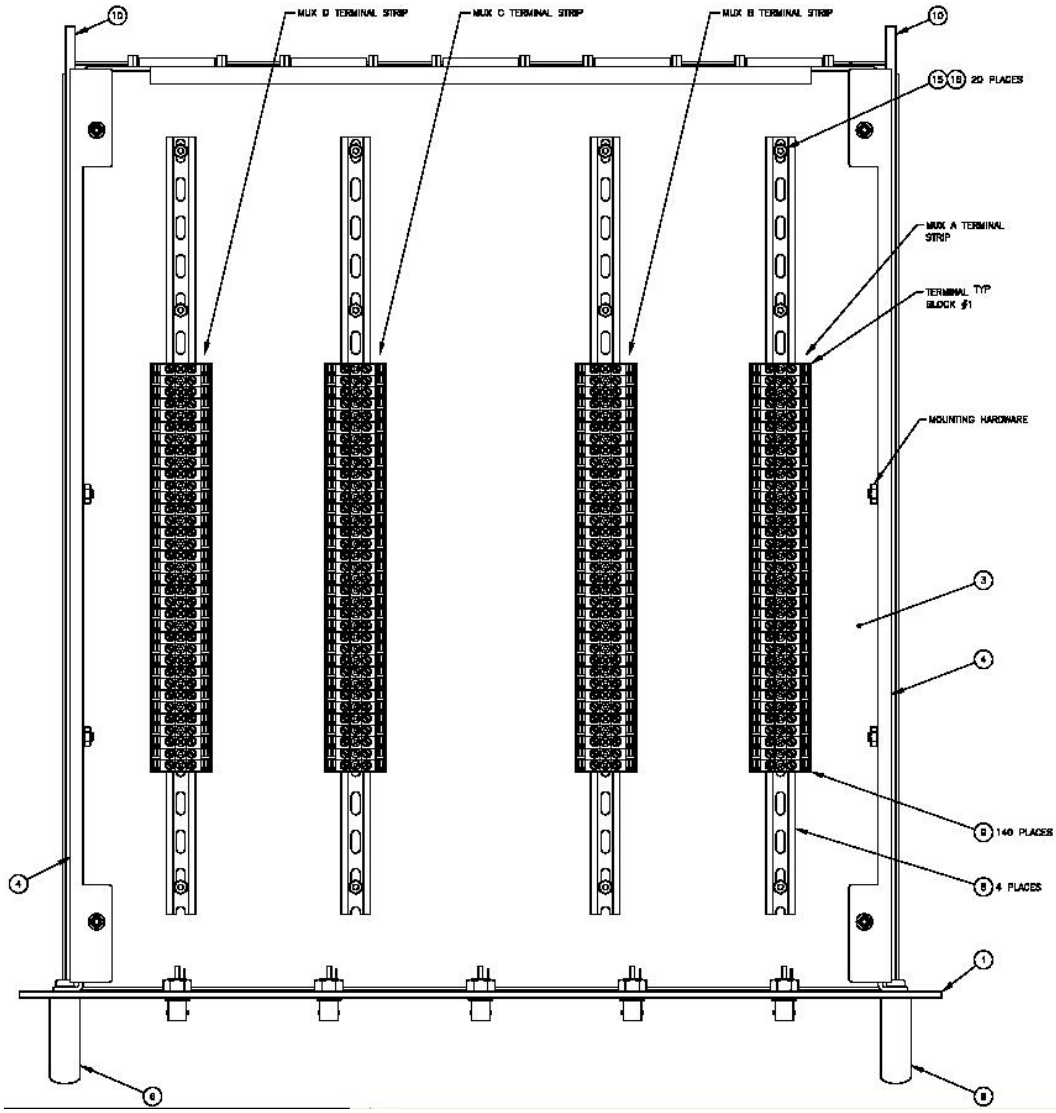

Figure 14 Top view of the multiplexer chassis box interior.

These interior connection points in the chassis box are also used to route signal wires from the coils to create a bucked coil wiring configuration prior to the signal exiting the chassis box. All signals are then routed to corresponding 25 pin D outputs connections at

the rear of the chassis box. These signal outputs are connected to the multiplexer. For each multiplexer bank, there are 10 input signals and one output signal. The output signal from the multiplexer is routed back to the chassis to the corresponding multiplexer chassis terminal strip. This output is finally connected to a single bank output BNC connection and a four bank sum BNC output connection on the front of the chassis box.

PDI Interface Module Micro Switches

The PDI unit can communicate with a host computer using either an IEEE 488 (GPIB) cable or a RS 232 serial connection. The decision was made to use the IEEE 488 connection based on available hardware, speed of data transfer, and GPIB code examples for the PDI module. To configure the PDI for communication a series of micro-switches must be set. Figure 15 shows the configuration currently used in the JLab measurement system.

1	0
2	1
3	1
4	1
5	0
6	0
7	0
8	0
9	1
10	0

Figure 15 PDI 5025 Microswitch Configuration for GPIB

PDI Wiring

Encoder Wire

The encoder wire uses a 5 pin connection detailed in the PDI Manual. The current motor timing is A and B low when I is high. Also, the encoder wire index must be left open.

Motor Wire

Currently not used. Motor is run externally by a National Instruments stepper amplifier.

Coil Input Wire

The coil input wire uses a 4 pin connection detailed in the MetroLab PDI Manual. Currently the factory preset is being used with jumper J3 in place (balanced with input impedance 2M Ohm).

Jumpers

Trigger Module

- J1 moved to 2-3 for Encoder 'A' channel negative polarity.
- J2 moved to 2-3 for Index negative polarity. (after testing: index not used, use external sync)

Motor Amplifier

The National Instruments MID-7602 is a multi-axis power amplifier interface used to power both the rotational and linear motors of the integrating system. Axis 1 is used for the rotating coil stand. Axis 2 will be used for a future translating wire stand.

The MID-7602e is used along with the FlexMotion FW-7344 controller. The Motor wiring configurations are:

Motor

1	2	3	4	5
Clear	**Green**		**Red**	**Black**

Encoder

Axis 1

1	Brown
2	**Yellow**
3	**Red**
4	**Black**
5	**Orange**
6	**Blue**
7	**White**
8	**Green/Ground**

PDI Encoder Tie in to Encoder Connector

1	Brown
2	
3	**Green**
4	
5	
6	
7	Grey
8	**White**

Note: Yellow *Index* wire must be disconnected when using the external trigger

Limits
Axis 1

- Red = Forward
- White = Reverse
- Black = Home

1	**Red**
2	**Black**
3	**White**
4	
5	Ground
6	**Green**

FW-7344

The FW-7344 motion controller is connected to the host computer using a firewire connection. From the FW-7344, a NI stepper wire is used to deliver its signals to the motor amplifier. Because the stepper connection wire does not provide a path to any of the four DAC's included on the FW-7344, an external connection was added to the unit. This connection provides access to DAC channel 3 (+/- 10V). A simple controller can be accessed from the startup screen of the Jlab integrating software program (the "Control Analog Output" button). The FW-7344 Hardware Manual can be found in the MagTest\Documents folder. Software information can be found through the Measurement and Automation Explorer help file.

Signal Chassis Box Detail

A chassis box was constructed to allow the measurement system's input signals to be routed to a single output BNC connection. Signals can be connected in a bucked configuration, as seen in Figure 16, inside the chassis box before being routed to the multiplexer. From the BNC output, the signal is connected to the PDI. The chassis box works in conjunction with the Keithley multiplexer and will be able to handle inputs from up to four different measurement stands. Figure 17 shows the signal breakout typical of each multiplexer bank.

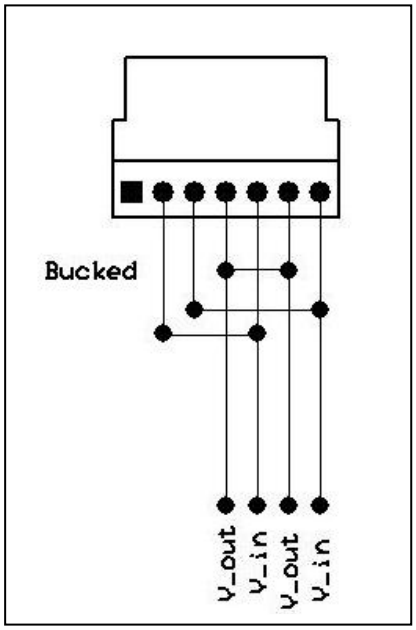

Figure 16 Bucked signal wiring configuration. The positive leads of the induced voltage signal from each winding are routed to a separate channel and the return leads are wired together to cancel the quadrupole signal and allow higher resolution harmonic analysis.

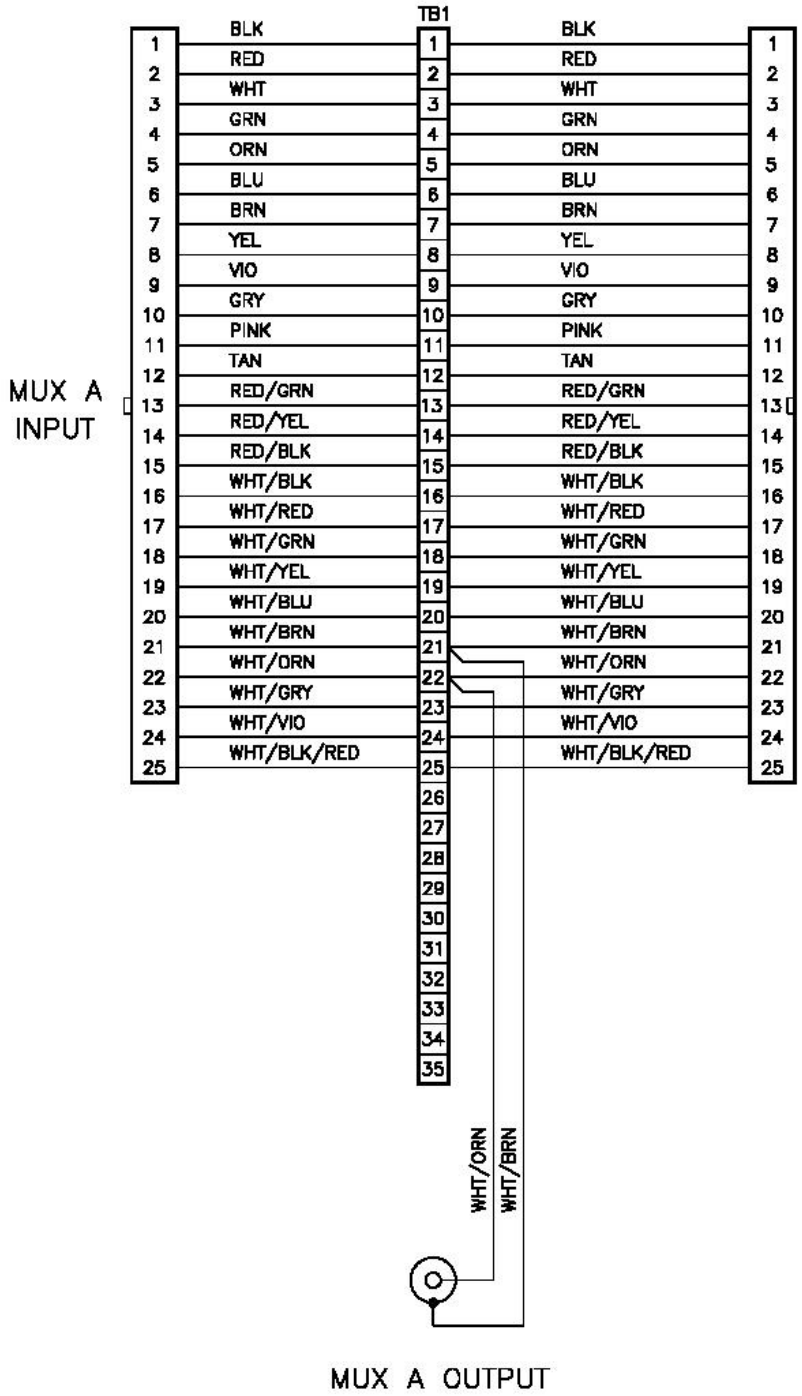

Figure 17 Signal Chassis Box Wiring Breakout Configuration

Motion Control Setup for Motor

To configure the motion controller, import settings from the file menu. A working configuration is stored on the network drive in "m:\magtest\software code\Flex Motion\ Saved Settings For Rotating Coil motor.xml". To open the folder, click here

The FW-7344 motion controller is used in conjunction with the motor amplifier. It is connected to the host computer using a Firewire connection. From the FW-7344, a specialized NI motor communication cable is used to deliver its signals to the motor amp. Phoenix connectors are used to connect the motor and encoder wires to the amplifier. This allows signals to be sent and received between the motor amplifier and the motor.

To reset the controller using Measurement and Automation Explorer setup the Axis and Encoder configurations and then initialize the device as shown in Figures 18 and 19.

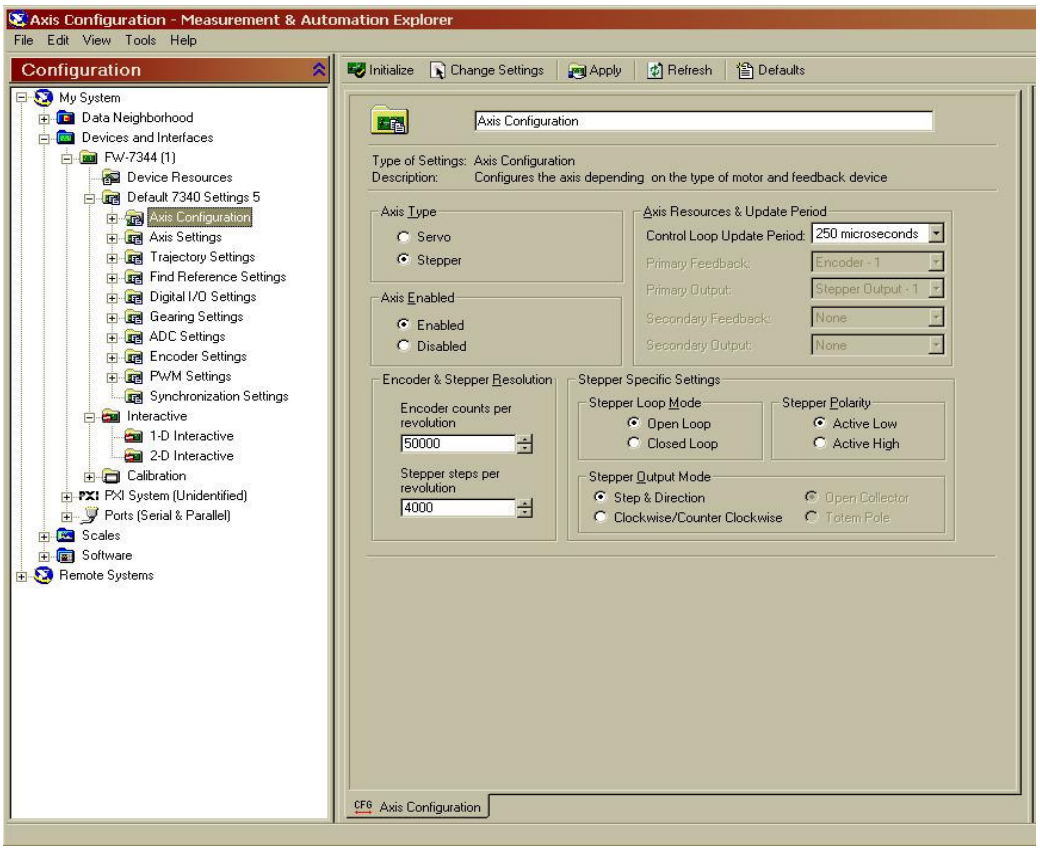

Figure 18 IP MAX axis configuration for motor controller and encoder

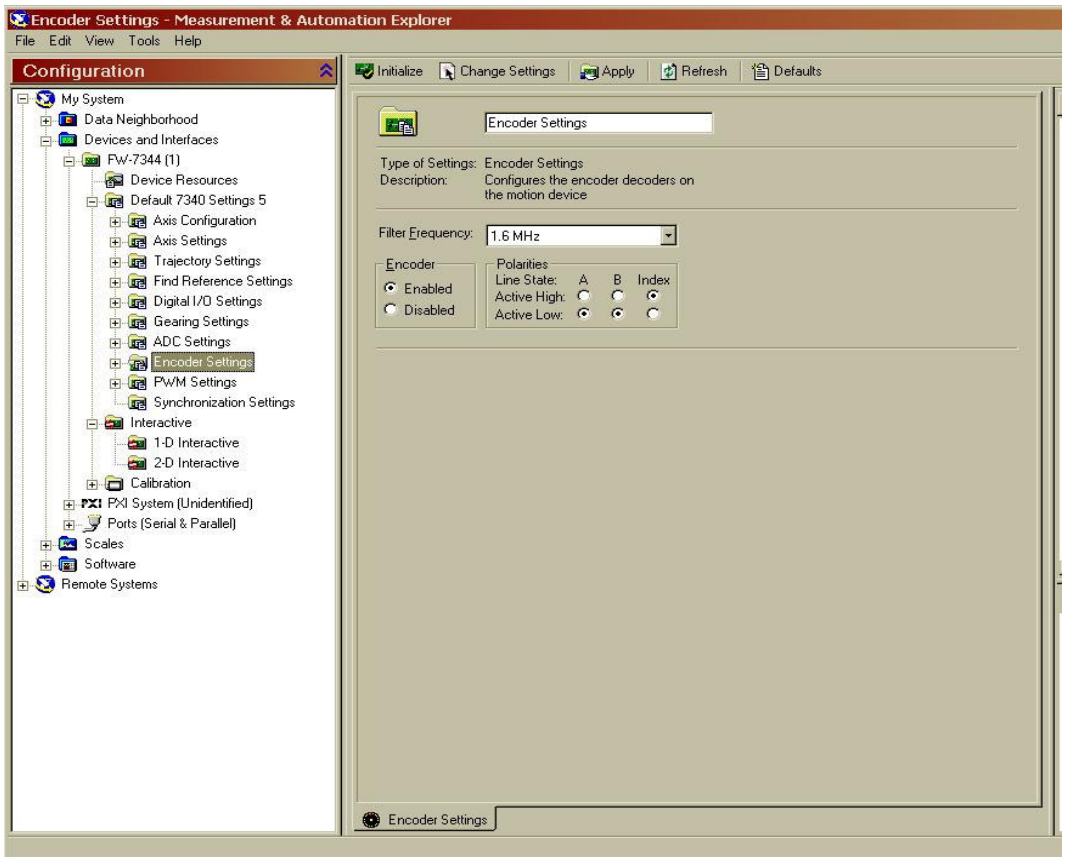

Figure 19 MAX instrument initialization

Motor Setup

In a typical measurement rotation, the motor pointer will be positioned approximately at the start position shown in the following diagram. The motor will rotate clockwise (PDI Fwd) for the '+' measurement and counter clockwise for a reverse measurement. An example PDI command to set up a measurement for 100 readings would be:

- FWD: TRI,+,0/100,40

- **Meaning:** *Trigger the Reading Intervals, while the motor is moving PDI forward, start at the 0 sync signal, take 100 reading, spaced 40 counts apart.*

- REV: TRI,-,4000/100,40
  - **Meaning:** *Trigger the Reading Intervals, while the motor is moving PDI Reverse, start at 4000 counts forward from the 0 sync signal, take 100 reading, spaced 40 counts apart.*

When using external sync the first sync received after the "IND,S" command will be considered zero. Therefore, absolute position (in number of pulses) must be set for the reverse measurement. In this case, we want to take 100 sample spaced 40 counts apart (4000 counts total). Because the forward measurement is taken first, the reverse measurement is started at a 4000-count offset from the forward measurement.

Jumper J2 must be put on pins 2-3 in the PDI rack 5140 Trigger slot and "TRS,E,S" and "SYN,1" must have been sent.

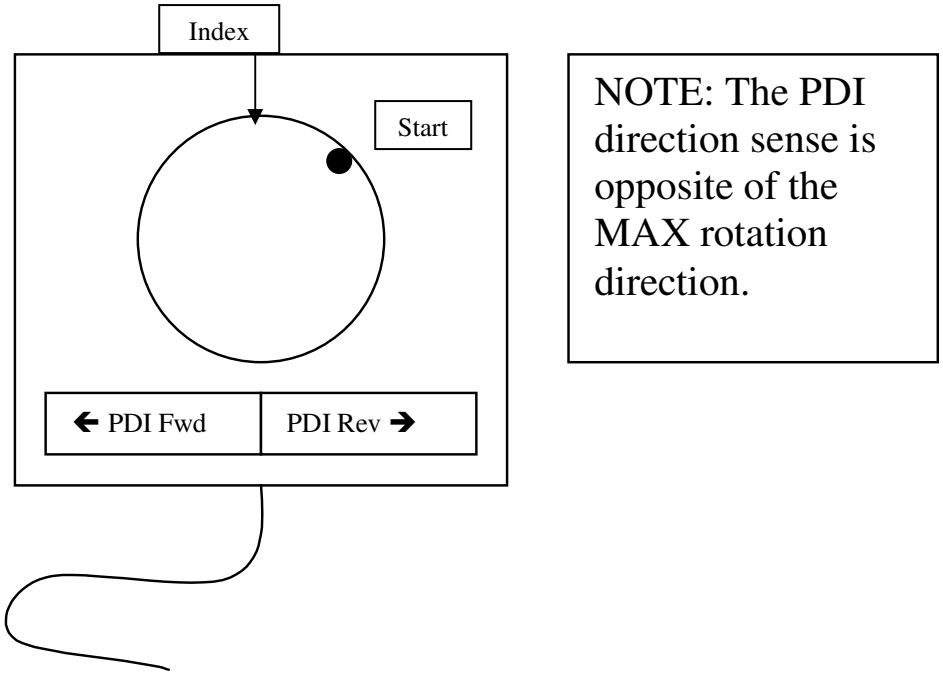

Figure 20 IP Motor trigger and index location

Component Channels

Table 1 shows the current GPIB addresses used in the multipole measurement system for communication.

Component	GPIB Channel
HP34970A	9
K7011	16
PDI5025	14
Boss Pwr Supply	6
GPIB Board	0

Table 1 GPIB instrumentation channels

GPIB ENET/100

The GPIB-ENET/100 is used to communicate GPIB commands through an Ethernet connection. This functionality decreases cabling restrictions and adds the ability to communicate with your GPIB instrument from any location in the world that has an Ethernet connection. Each GPIB ENET/100 in the Magnet Measurement group will have it's own unique IP address and host name. These attributes are used to set up the GPIB ENET/100. The GPIB ENET/100 requires NI-488.2 (or higher) to be functional. When installing the software the user will be required to remove older, incompatible GPIB drivers before installing NI-488.2. Once the software is installed you must hook up the GPIB ENET/100 power and Ethernet connections and configure the device.

The current GPIB ENET/100 device configuration is shown in Figures 21 and 22. Refer to the GPIB "Getting Started with your GPIB-ENET/100 and NI-488.2" manual for detailed instructions on device configuration.

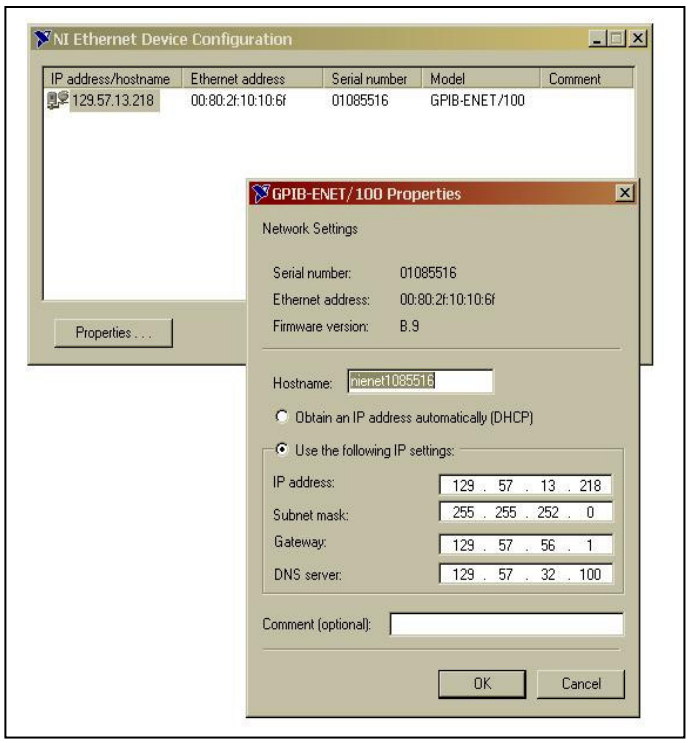

Figure 21 IP Configuration for GPIB ENET/100

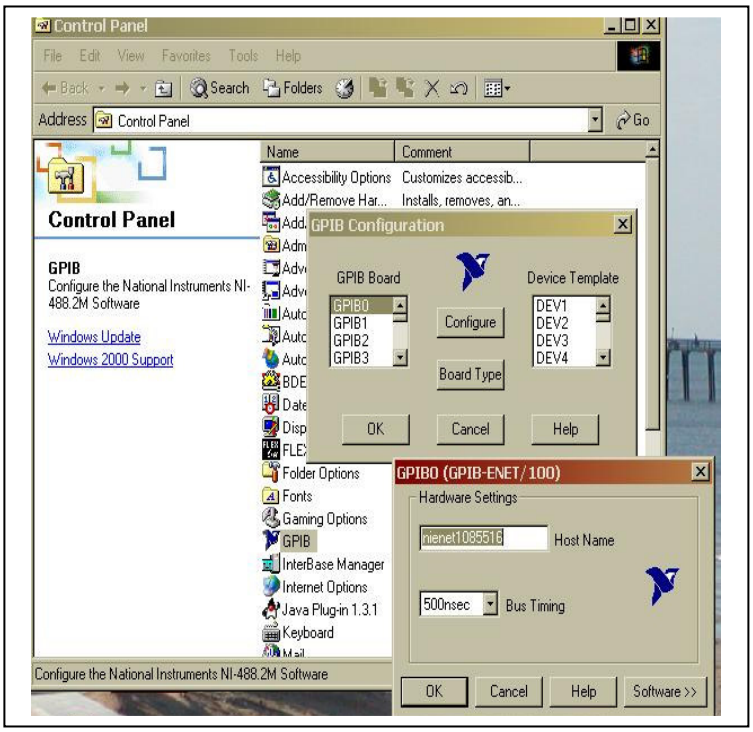

Figure 22 GPIB ENET/100 Setup

Harmonic Measurement Probes

There are five distinct harmonic coil probes that are available for use in the rotating coil measurement system at JLab. Each coil is fabricated for use with magnets of varying lengths and bore sizing. Initial testing was done using a 1" measurement probe, P1A. This probe has a radius of 1.120" and has two coils which can be bucked, or canceled, against one another, to suppress the main field component. In this way the resulting signal can then be used to evaluate the field quality with increased sensitivity.

Accuracy in absolute magnetic field strength measurements cannot be achieved without precise physical magnet alignment of the probe and magnet. In magnets where there exists a horizontal field gradient, error in measured field strength will result from any error in the horizontal probe position. For example, in a magnet with 10% horizontal field gradient, measurement of the field strength to 1 part in 10^4 requires positioning the probe with 0.1 mm accuracy.

Another issue effecting measurement accuracy is measurement system construction. The typical manufacturing and measurement uncertainty for magnetic measurement apparatus is ~0.001" (25 μm) which translates into a field error of 3 parts in 10^3 for a probe of 10 mm maximum radius. To meet the goals of the new magnet measurement system, 1 part in 10^3 is required. This level of precision can only be achieved using a calibration magnet. In this case the calibration (or standard) magnet absolute strength must be known as well or better than the required precision of the subject magnet measurement. Currently, JLab does not have a standard magnet for absolute calibration. There is a

possibility that an electromagnet could be precisely measured at an external facility and then used as the standard magnet for the JLab measurement system. Ideally, a permanent magnet will be purchased to be used as the standard magnet.