Cryomodule Magnetic Field Measurements

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Abstract

Superconducting Radio Frequency Cavities (SCRF) are being used in modern accelerators because of their high acceleration gradient and efficiency. Field emission threshold and quench however, limit the accelerating gradient thus degrading their performance. Quench is specific to superconductors and is dependent on temperature and magnetic field strength. In order to reduce the quench limitation and to support higher field gradients, the residual magnetic field in the SCRF has to be kept minimum. The cavities are magnetically shielded to prevent magnetic flux from being trapped in the cavities during cool down. The cryomodule~~s~~ vessel shields the cavities from the earth's magnetic field. In addition, each cavity is shielded by an independent mu-metal shield. To ensure that the residual magnetic field inside the vessel is acceptable, we develop a LabVIEW measurement program to measure the residual magnetic field along the length of the inside of the vessel where the SCRF cavities will be mounted. The LabVIEW program reads Bartington's Mag-03MC1000 Flux-Gate magnetometer using National Instrument's Data Acquisition hardware to measure the magnetic field inside the cryomodule.

Keywords: Cryomodule, Magnetic field, Magnetometer, LabVIEW, Superconducting RF cavities.

1. Introduction

1.1 Fermilab

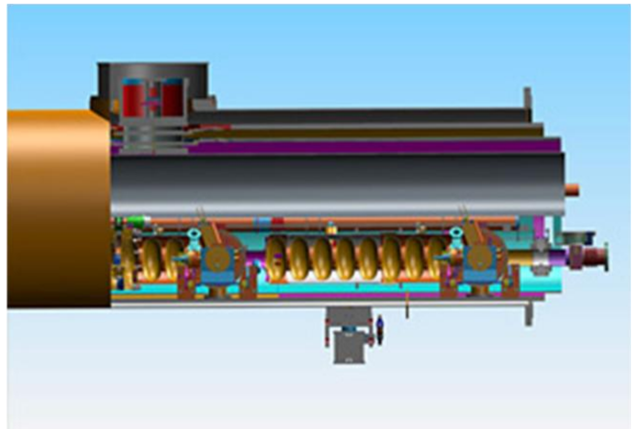
Fermi National Accelerator Laboratory enhances the understanding of the nature of matter and energy by providing the resources for researchers to conduct research in high energy Physics and other related disciplines. Among the many divisions on site is the Technical Division where I interned this summer in its Test and Instrumentation department. This department performs measurements and tests of both R&D and production accelerator components, and develops technologically advanced instrumentation, control solutions, and cryo-mechanical systems for accelerator applications. Here, I spent some weeks of the summer performing calibrations of instruments used for testing superconducting magnets and updating the calibrations database. I also spent some weeks learning how to design power circuit boards using Altium Designer beginning from schematic design, while the rest of the summer was spent writing and testing a LabVIEW program to be used in carrying out magnetic field measurements inside the cryomodule with data acquisition hardware. This paper will focus on field measurements inside the cryomodule. The appendix will discuss the other two projects succinctly.

1.2 International Linear Collider (ILC)

Fermilab is positioning itself as a key contributor in the construction of the proposed accelerator, the International Linear Collider (ILC). This project is critical in discovering what the universe is made of and how it works. It will accelerate electrons and their opposites, positrons, close to the speed of light. In order to provide the necessary acceleration to make particles collide at 500 billion electron volts, the ILC will use Superconducting Radio Frequency Cavities (SCRF) made of pure niobium that are chilled to 1.8 degrees above absolute zero. As many as 16,000 nine-cell 1.3GHz cavities, each roughly a meter long and placed end-to-end in vessels called cryomodules (figure 1), will drive the electrons and positrons forward with an accelerating gradient of more than 30 million volts per meter (MV/m) in each 9-cell cavity. The accelerating gradient is a measure of how much an accelerator can increase the energy of a particle over a certain stretch, typically given in Volts/ Meter. The higher the gradient, the shorter, and hence cheaper, the ILC can be made. The lab fabricates and tests the superconducting cavities required for this project.

a

b

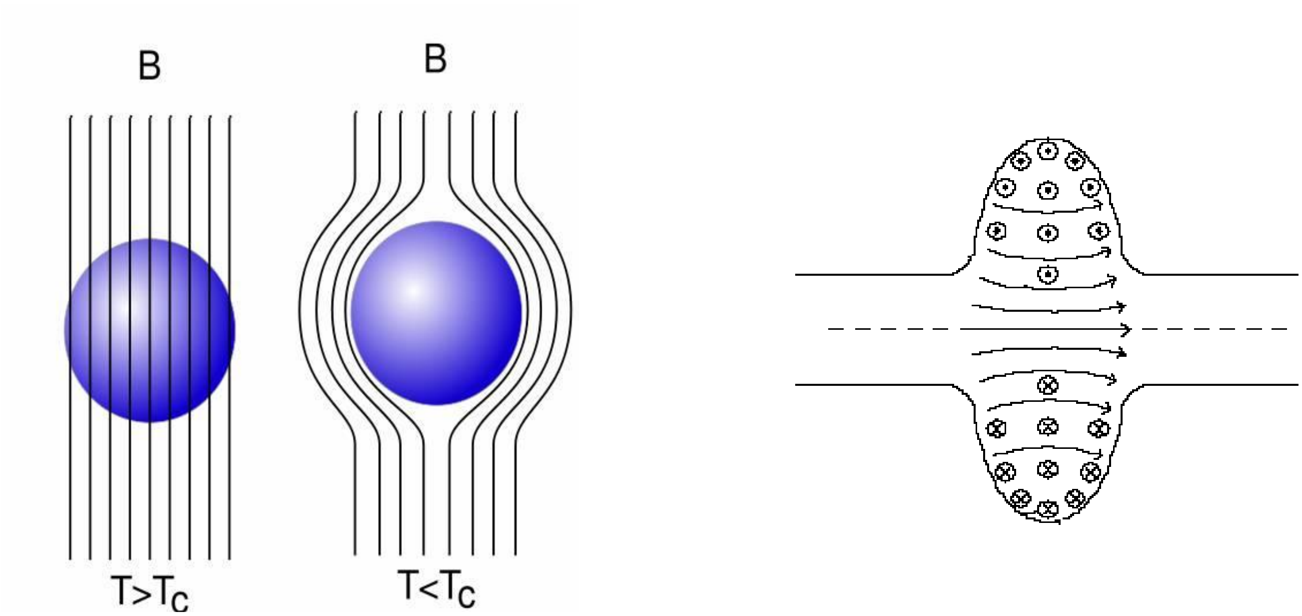


http://ilc.fnal.gov/accelerators/cryomodule.html

Figure 1: 1.3 Ghz Cryomodule. (a) Empty Cryomodule, (b) an inside view of Cryomodule with the superconducting cavities

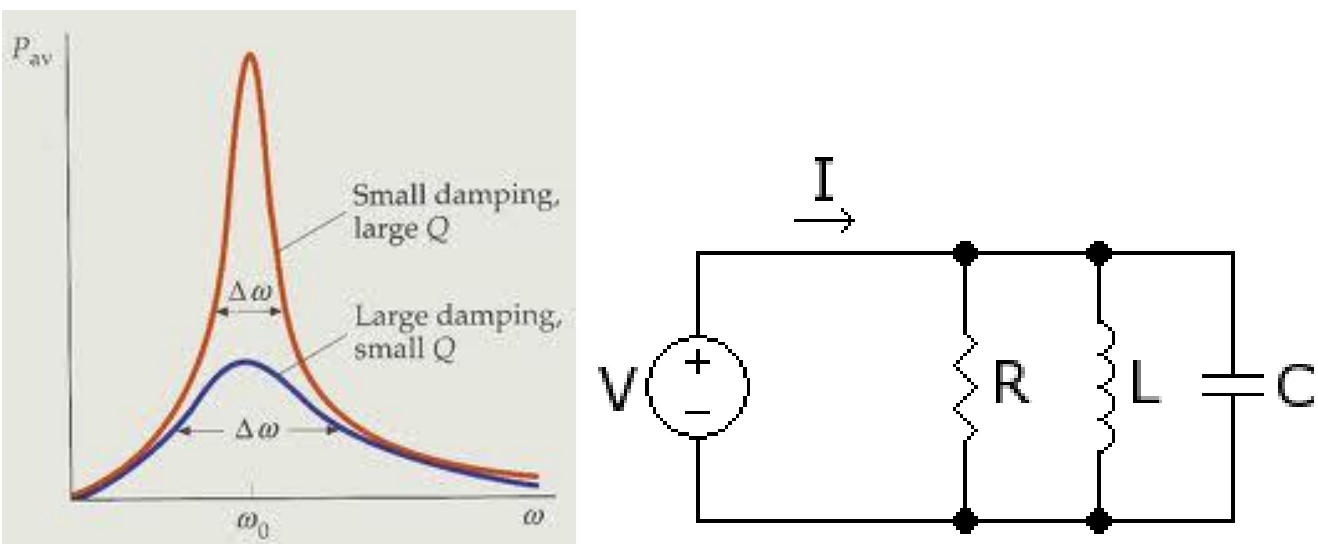
1.3 Superconducting RF Cavities

When some materials, such as Niobium, are cooled to a very low temperature, they have no electrical resistance therefore becoming superconducting. The temperature at which electrical resistance is zero is called the critical temperature and varies from one material to another. At these low temperatures charge carriers condense into cooper pairs which move without friction hence zero resistance. At zero Kelvin, all charge carries condense. At high temperatures the pairs break up. The fraction of unpaired carriers increases exponentially with temperature, $e^{-\Delta/KT}$, until none exists above the critical temperature [6]. Because these materials have no electrical resistance they can carry large amounts of electrical current for long periods of time without losing energy as heat. Meissner and Ochsenfeld discovered that superconductors expelled the applied magnetic field from their interiors. They found that if a material was cooled into the superconducting state and then exposed to an external magnetic field, the field would not penetrate the interior of the material until the field reached the critical value (at the particular temperature) [2]. This phenomenon is known as Meissner effect and is demonstrated by Figure 2(a) below.



(a) *(b)*

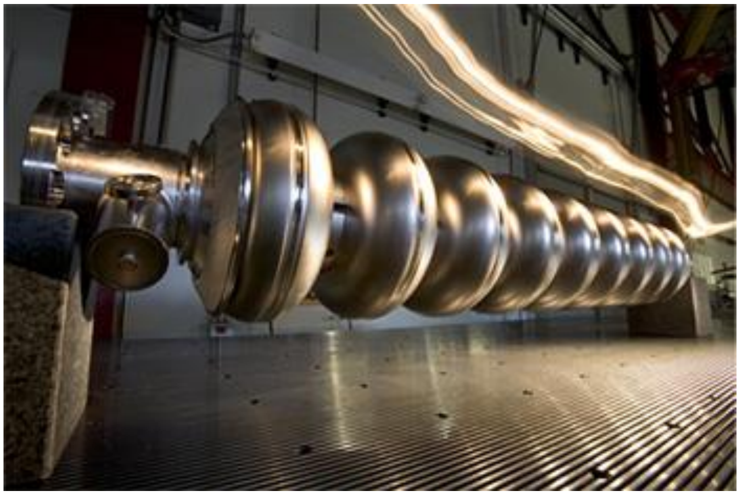
Figure 2: (a) Meissner effect, when temperature is greater than critical temperature (no superconductivity) field passes through the material normally, when the temperature is less than critical temperature, the magnetic field is excluded from the material [7] (b) Superconducting RF cavity beam acceleration[12]

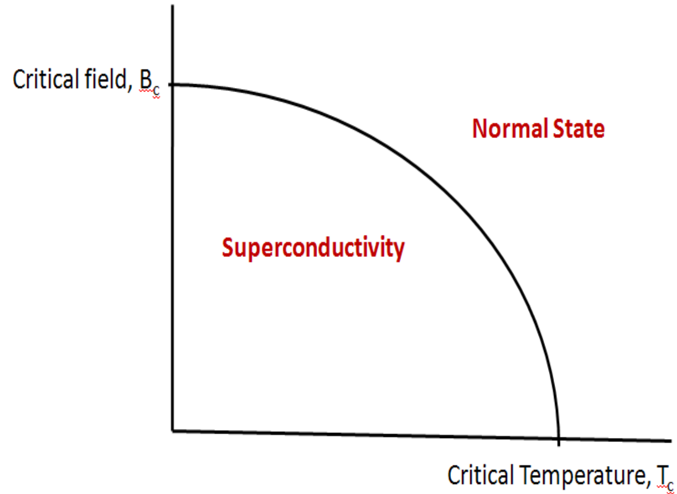


(a) (b)

Figure 3: (a) Resonance Curve [13] (b) Simple RLC circuit [12]

Superconducting Radio Frequency cavities (SCRF) technology uses hollow structures called cavities to drive particles to higher energies (figure 2(b)). The cavities are made from smooth cells of Niobium (figure 4(a)), carefully electron beam welded together to form 9 cells. The cavities are electrochemically polished to provide a mirror-like surface. The surface must be free of fine particles and surface blemishes. Defects at the level of a few microns can cause cavities to lose their superconductivity and quench so that they cannot sustain the electric field needed to accelerate particles. Chemical polishing, electro-polishing, high pressure water rinses and heating at high temperatures are proven effective treatments for achieving high accelerating gradients in superconducting cavities [4]. Heat treatment cleans Niobium from Hydrogen which was picked up during electrolytic polishing. Cavities with elliptical cross section are preferred because of their advantage to suppress another undesirable performance limitation called multipacting, the resonant multiplication of electrons via the acceleration in the RF fields and secondary electron emission upon impact on the surface [4]. Another fundamental advantage of superconducting cavities is the extremely low surface resistance of about 10 n at 2 K [5]. These Superconducting RF cavities work on the same principle as simple RLC circuits but with high frequency. RLC circuit forms a harmonic oscillator and resonates at specific frequencies. Resonance occurs because the circuit consists of two energy storage devices, the capacitor and the inductor with energy being transferred from one to the other causing oscillations. The capacitor stores energy in the form of an electric field as it gets charged ($E= 1/2QV$) while the inductor stores energy in the form of magnetic field as the current flows through it ($E= 1/2LI^2$). The presence of a resistor damps the circuit and completely stops the oscillation if there is no driving voltage source. The quality factor(Q), the ratio of energy stored to the energy dissipated at resonance per cycle, is the term used to characterize a resonant system and is given by, $Q= f/\Delta f$ where f is the resonance frequency and Δf is the bandwidth, both shown in figure 3 above. Similarly the superconducting cavities technology is an oscillating system where energy is also stored in electric and magnetic fields. During resonance, a standing wave is set up inside the cavity where the electric field is in the direction of acceleration and charged particles entering the cavity get accelerated. They have extremely high quality factors of about 10^10 to 10^11. In these cavities, the width of resonance curve at frequencies of the order of GHz is very narrow and ranges from 0.1 to 0.01Hz resulting in the high quality factors.





(a) (b)

Figure 4: (a) RF Superconducting Cavities made from smooth cells of Niobium [3], (b) Superconducting curve

1.4 Effect of magnetic fields

Despite the great performance of the RF Superconducting Cavities technology field emission and quench limit its performance. Quench, a characteristic specific to superconductors, is the breakdown of superconductivity and occurs when the critical field and critical temperature are exceeded as shown in Figure 4(b). Beyond these critical values, the cooper pairs resulting in superconductivity break up making the cavities lose their superconductivity. If the field on the surface of the cavities exceeds some limit, magnetic flux will be trapped within the cavities during cool down increasing the field inside the superconductor. This greatly reduces the maximum achievable accelerating gradient. Trapped magnetic direct current flux results in a surface resistance [5][8]

$$R_{mag} = (B_{ext}/2B_{c2})\, R_n \qquad 1.1$$

where B_{ext} is the externally applied field, B_{c2} is the upper critical field, and R_n is the surface resistance in the normal state [5][9]. To reduce this, the vacuum vessel which is to hold the cavities, has been shielded using soft iron to reduce the magnetic field experienced by the cavities. As part of the testing of these cavities, we therefore need to measure the field as a function of distance inside the vacuum vessel which will hold the cavities to ensure that the residual field is within some limits.

2. Tools and Methods

To measure the magnetic field, we use a magnetometer together with National Instruments' data acquisition hardware. We wrote a LabVIEW program to be used with these instruments to measure the field. The following sections discuss the function of each of the instruments and how the LabVIEW program works.

2.1 Magnetometer

Magnetometer (Magnetic Sensor) is an instrument which measures the strength and/or direction of the magnetic field in its vicinity. We use Bartington's Mag-03MC1000 three gate magnetic field sensor which has a cylindrical enclosure and a range of $\pm$1000μT. The three axis magnetic field sensors provide measurements of static and alternating magnetic fields in three axes. The sensors, alternatively described as magnetometers, convert magnetic flux density, measured in three axes, into bipolar analog output voltages V_x, V_y, and V_z, which are in linear proportion to the flux density [10]. Three fluxgate sensing elements are mounted orthogonally at one end of an enclosure which also contains the electronic circuitry. The connector is mounted at the opposite end of the enclosure. The sensors require a power supply of between ±12 and ±17V and provide three high precision analog outputs of 0 to ±10V full scale, proportional to the magnetic field along each axis. The sensor is powered by Mag-03PSU (power supply unit) via the mains adapter provided or from the internal rechargeable battery.

2.2 Power Supply Unit (Mag03PSU)

This unit provides a battery backed power supply of 12V for the Mag-003 series of three axis fluxgate magnetic sensors. The Mag-03PSU also contains high and low pass filters for the analog signals from X, Y and Z axes of the Mag-03 sensor. The low pass (<4.5 kHz) filter removes high frequency noise from feed through of the sensor excitation frequency and any external sources. The high pass filters have a fixed low frequency cut off at 0.1Hz and are intended to isolate the DC or static field component so that the alternating components above this frequency can be measured or analyzed [1]. This unit is connected to the sensor via a 10m long cable. The cable carries the supply voltage to the magnetic field sensor; 0V connection is via the screen. Analog signals are returned via three conductors and the analog return via a common conductor.

2.3 National Instruments' Compact DAQ 9172 and 9239

National Instruments' Compact DAQ-9172 (NI cDAQ-9172) is an eight-slot USB chassis designed for use with C Series I/O modules (figure 4). It integrates a group of measurements into a single device that outputs all of the data via a USB cable. It is therefore capable of measuring a broad range of analog and digital I/O and sensors using a High Speed USB 2.0 Interface. NI 9239 modules (figure 5) used for this experiment are 4-channel, 24-bit simultaneous Channel to Channel Isolated Analog input modules. Each Channel provides an independent signal path and Analog to Digital Converter (ADC). Input circuitry for one of the NI-9239's channels is as shown in figure 6. NI 9239 uses a combination of analog and digital filtering to provide an accurate representation of in-band signals while rejecting out-of-band signals [11].

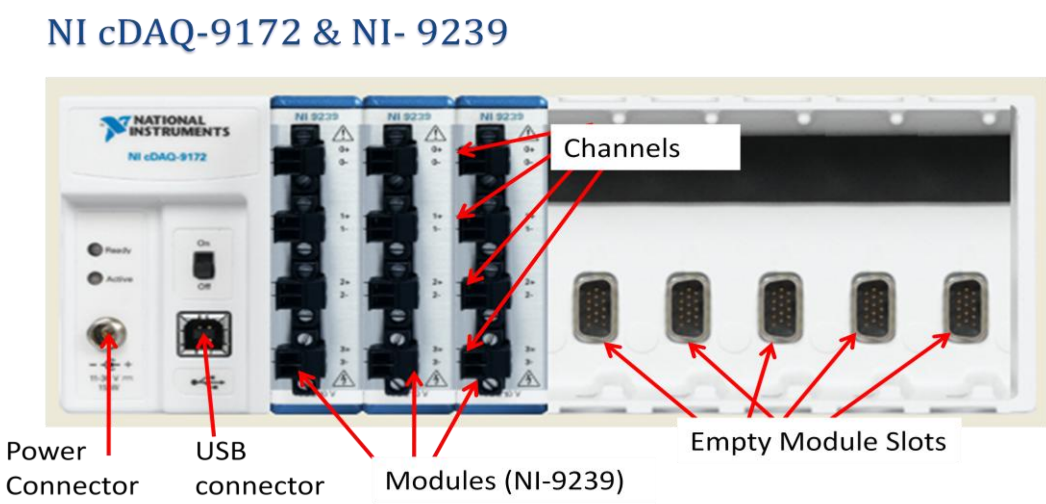


Figure 5: NI's compact Data Acquisition Chassis with NI's 9239 modules

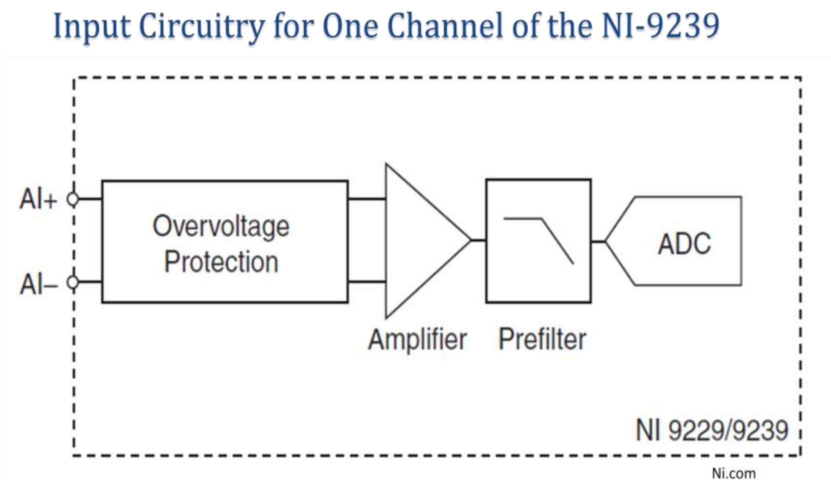


Figure 6: Input circuitry for one channel of the NI-9239 module [11].

2.4 Field Measurement program

The program was written in National Instrument's LabVIEW software. LabVIEW, **Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench, is a graphical programming environment used to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. LabVIEW contains a comprehensive set of tools for acquiring, analyzing, displaying and storing data. LabVIEW programs are called virtual instruments (VI). LabVIEW VI has both a front panel, which contains the controls and indicators (figure 7), and a block diagram which shows how all the controls and the indicators fit together as well as the hidden modules where the work gets done (figure 8). Controls are the 'output' they give outputs while indicators are 'inputs'. In LabVIEW, a program is executed in a dataflow left to right manner, each item executes only when all its required inputs are available. All looping and ordering is done by structures. Every control and indicator has an associated data type that determines what kind of data flows from or to it on the block diagram. Every data type also has an associated color shown on the block diagram. Structures modify the sequence of data flow on the block diagram. There are currently six structures supported by LabVIEW, while-loops, case structures, event structures, for-loops, sequence structures and formula nodes. The diagrams below show the front panel (figure 7) and the block diagrams (figure 8) of the program. The program does four main things, it works with the data acquisition hardware to collect the magnetic field measured by the sensor, averages each of the field axes over the given number of samples, calculates the magnitude and plots it for the given distance along the cryomodule, steps the distance automatically and appends the data collected at a given point to a file. The resulting file can be opened in excel and contains X, Y and Z magnetic field and its corresponding magnitude, distance and other details like date and time the measurements were taken as well as any user provided comments. A progressive plot of the field magnitude at different data points as the sensor moves along the cryomodule is also observed and can be saved at the end of the experiment by right clicking on it. To measure the field, the user needs to provide the information required to run the program as shown in the front panel. The user needs to specify the data path where the output file will be saved to, the desired step size, start distance, stop distance, the number of samples for which the measurements will be averaged over, the sampling rate, chosen so as to minimize noise as much as possible, and any general comments that the user wishes to include in the output file in the Header Comment text box. The user then pulls the sensor along the cryomodule as desired and clicks on the Execute & Write button which records the magnetic field at that point, plots the magnitude and steps the distance by the step size specified in the step size box.

2.5 Procedure to measure the field

A long Aluminum channel supported by wooden structures was installed inside the cryomodule where the cavities will be positioned (figure 9). The channel supports and guides the probe down the axis where the cavities will be suspended. The channel was installed on one half of the cryomodule since the sensor cable, which is 10m, is shorter than the 11.6 meter cryomodule. The magnetic sensor probe was supported by a G-10 probe holder that slides down the aluminum channel. The magnetic sensor was also attached to a tape measure to keep track of the location of the sensor, and placed on the aluminum channel at about the center of the cryomodule.

The sensor was then pulled outward along the cryomodule through small step sizes while taking the field measurements using the LabVIEW measurement program.

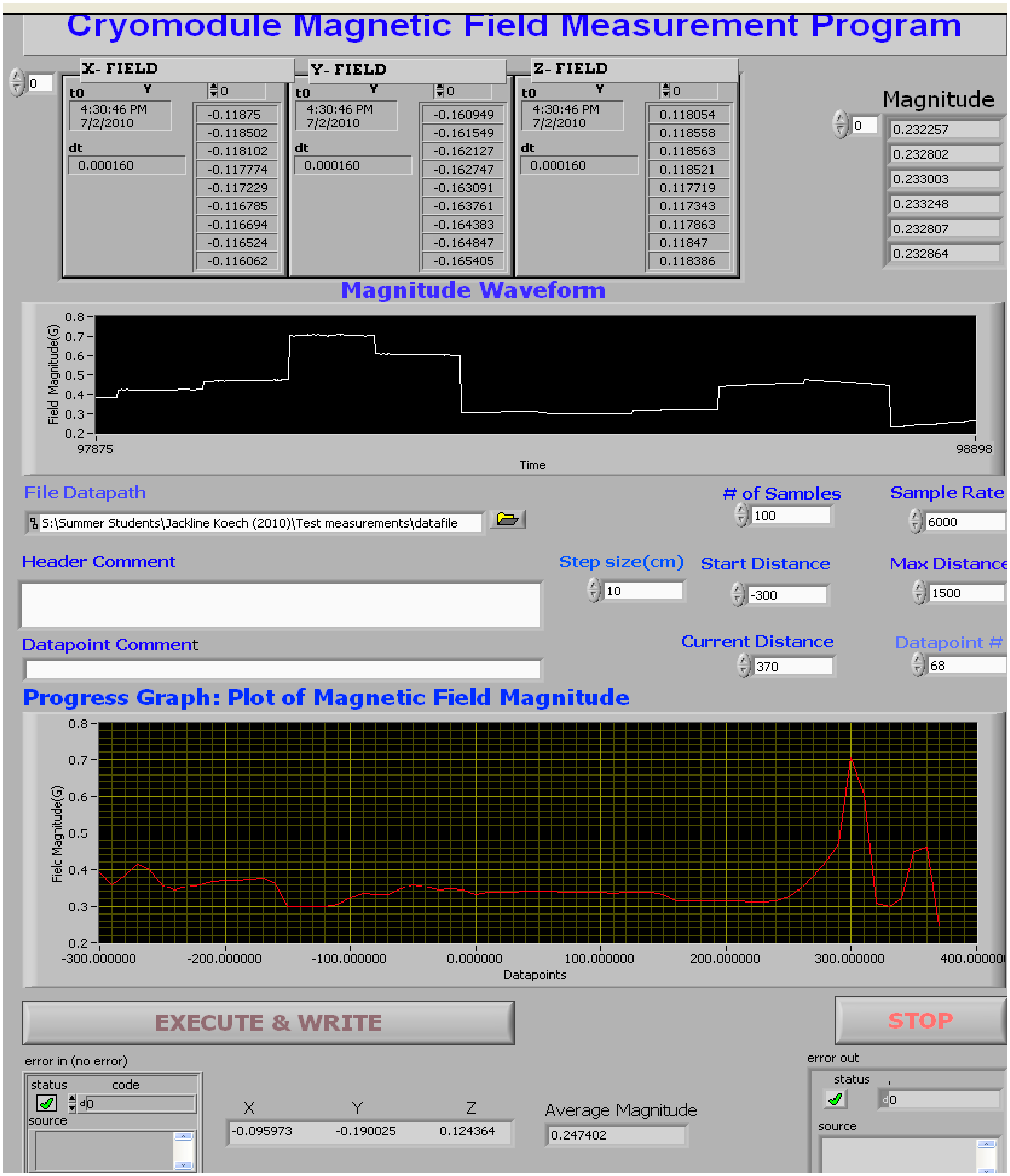


Figure 7: Front panel of the LabVIEW program, to run the program, provide information such as step size, file datapath etc, then move the sensor to the desired location and click on the Execute & Write button.

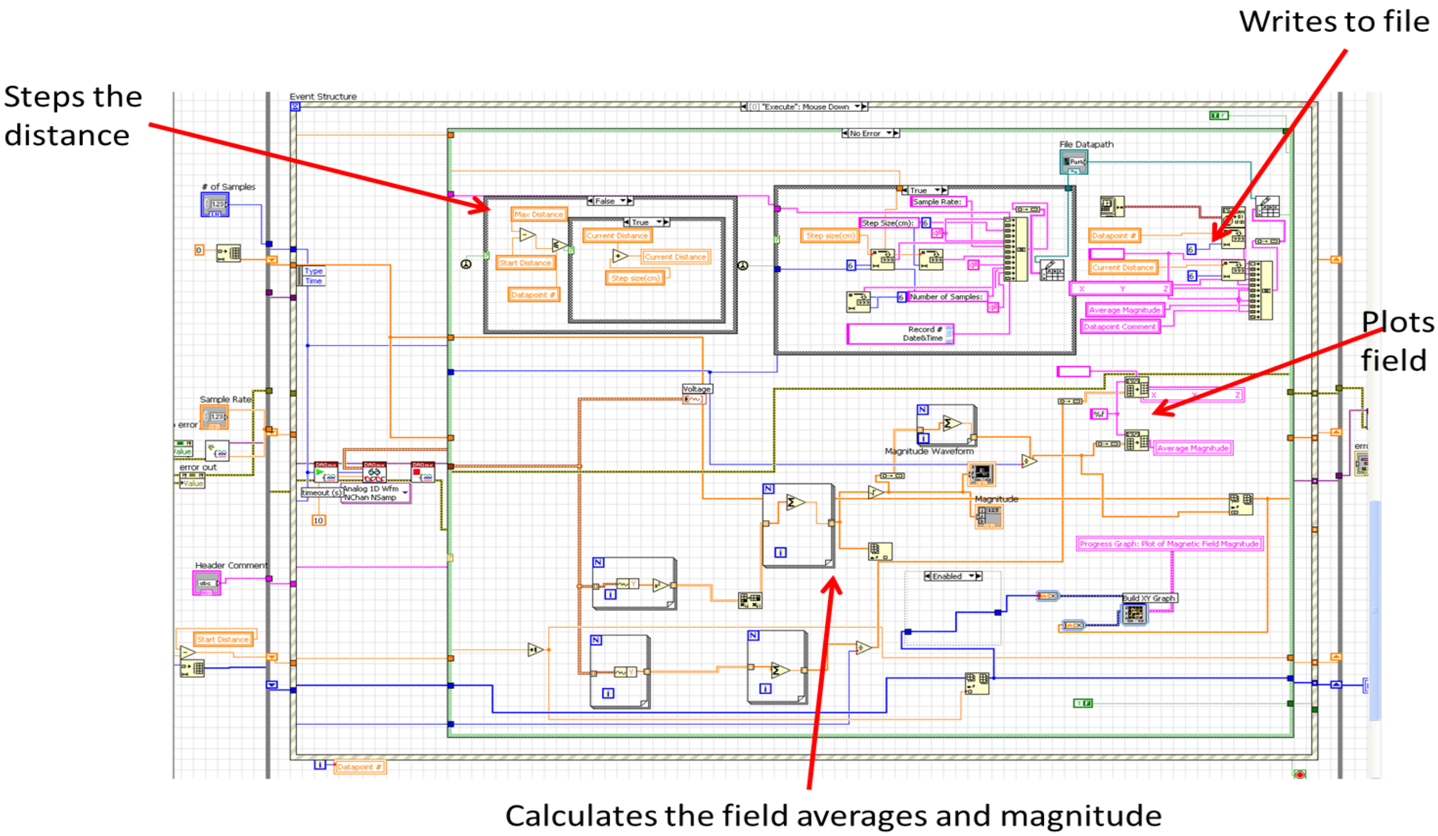


Figure 8: Block diagram of the LabVIEW program showing the Execute and Write Case Structure and the sections which performs different functions such as writing to file, stepping the distance, averaging and plotting the field.

We repeated these measurements several times and then moved the aluminum channel to the other end of the cryomodule, placed the sensor at the same central location and pulled the sensor towards the other end of the cryomodule while taking measurements. The diagram below (figure 10) shows the setup of the magnetometer, the power supply unit, the NI data acquisition hardware and the computer. The magnetic field measured by the sensor is transferred to the Power Supply Unit (PSU) via the cable. The PSU filters out the noise in the signal and transfers the three filtered signals to the computer via NI-9239 module which converts the individual signals to digital and the NI 9172 Compact DAQ chassis which integrates all the signals and transfers them to the computer via a USB cable. The LabVIEW program, on the computer then processes the data as discussed above and provides an output file which can be analyzed offline.

Figure 9: Experimental setup, Aluminum bar inside the cryomodule where the cavities will be installed and a tape was attached to the magnetic sensor to measure the distance along the cryomodule.

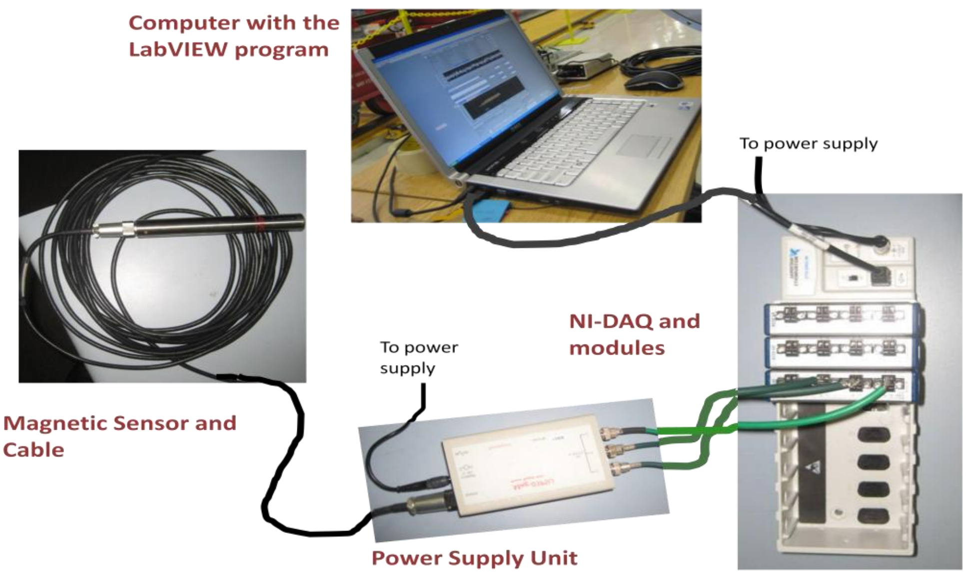
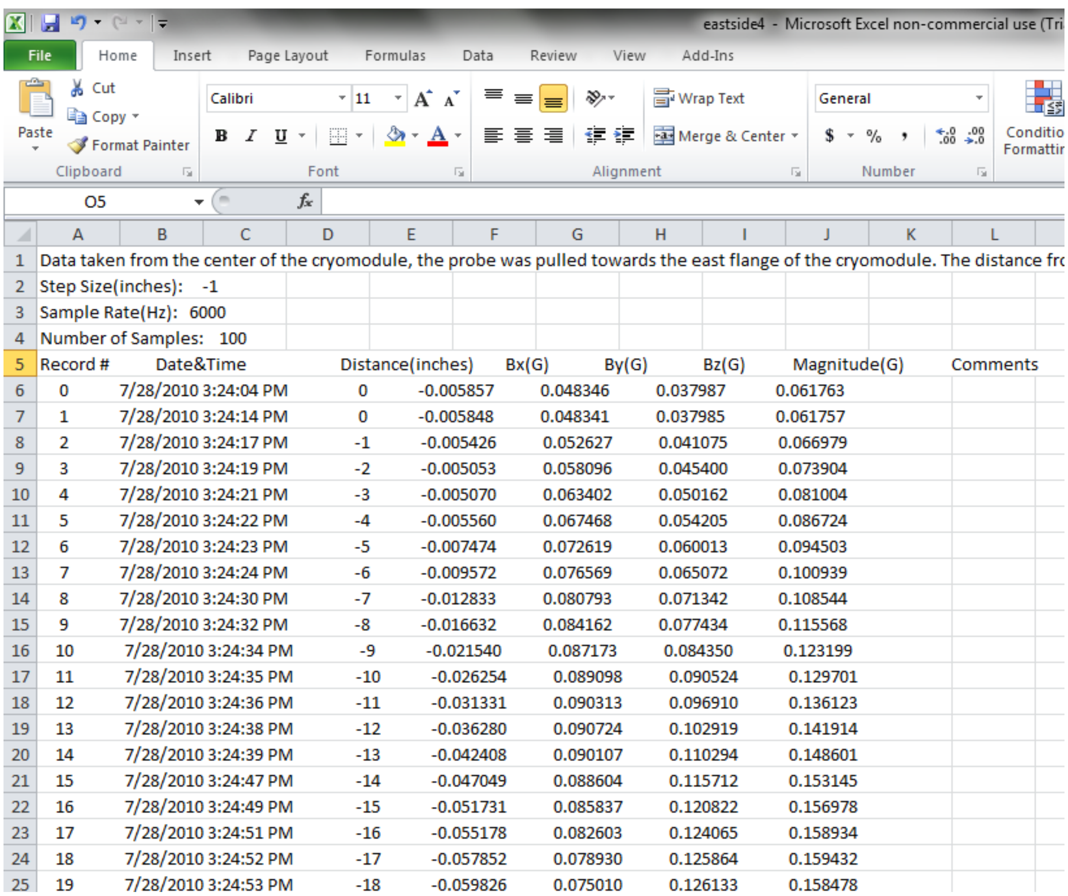


Figure 10: Experimental setup, magnetic sensor is connected to the DAQ via a 10m cable and a power supply unit. The LabVIEW program reads and writes data from the NI DAQ.

3 Results and Discussion

The figure below shows a sample output file opened in Microsoft Excel. The data contained in the file can be analyzed as desired, for example making plots of the X, Y and Z fields. We analyzed three pairs of measurements taken on either side of the cryomodule. The sensor was stepped through the cryomodule, one inch at a time. We plotted the magnetic field magnitude using the average of the three with standard deviation error bars as shown in figure 12 below. The magnitude was plotted against the distance along the cryomodule with -216 being beam entry side of the cryomodule also known as Flange K and position 236 is downstream end of the cryomodule, also known as Flange D. Position zero is the start point close to the center of the cryomodule where sensor was initially placed for measurements on both sides of the cryomodule. Outside the cryomodule we measure a field magnitude of about 0.5 Gauss as we would expect the earth's field to be. Beyond the ends of the cryomodule, the field inside the cryomodule decrease gradually to about 0.1- 0.2G.



Data taken from the center of the cryomodule, the probe was pulled towards the east flange of the cryomodule. The distance fr

Step Size(inches): -1

Sample Rate(Hz): 6000

Number of Samples: 100

Record #	Date&Time	Distance(inches)	Bx(G)	By(G)	Bz(G)	Magnitude(G)	Comments
0	7/28/2010 3:24:04 PM	0	-0.005857	0.048346	0.037987	0.061763	
1	7/28/2010 3:24:14 PM	0	-0.005848	0.048341	0.037985	0.061757	
2	7/28/2010 3:24:17 PM	-1	-0.005426	0.052627	0.041075	0.066979	
3	7/28/2010 3:24:19 PM	-2	-0.005053	0.058096	0.045400	0.073904	
4	7/28/2010 3:24:21 PM	-3	-0.005070	0.063402	0.050162	0.081004	
5	7/28/2010 3:24:22 PM	-4	-0.005560	0.067468	0.054205	0.086724	
6	7/28/2010 3:24:23 PM	-5	-0.007474	0.072619	0.060013	0.094503	
7	7/28/2010 3:24:24 PM	-6	-0.009572	0.076569	0.065072	0.100939	
8	7/28/2010 3:24:30 PM	-7	-0.012833	0.080793	0.071342	0.108544	
9	7/28/2010 3:24:32 PM	-8	-0.016632	0.084162	0.077434	0.115568	
10	7/28/2010 3:24:34 PM	-9	-0.021540	0.087173	0.084350	0.123199	
11	7/28/2010 3:24:35 PM	-10	-0.026254	0.089098	0.090524	0.129701	
12	7/28/2010 3:24:36 PM	-11	-0.031331	0.090313	0.096910	0.136123	
13	7/28/2010 3:24:38 PM	-12	-0.036280	0.090724	0.102919	0.141914	
14	7/28/2010 3:24:39 PM	-13	-0.042408	0.090107	0.110294	0.148601	
15	7/28/2010 3:24:47 PM	-14	-0.047049	0.088604	0.115712	0.153145	
16	7/28/2010 3:24:49 PM	-15	-0.051731	0.085837	0.120822	0.156978	
17	7/28/2010 3:24:51 PM	-16	-0.055178	0.082603	0.124065	0.158934	
18	7/28/2010 3:24:52 PM	-17	-0.057852	0.078930	0.125864	0.159432	
19	7/28/2010 3:24:53 PM	-18	-0.059826	0.075010	0.126133	0.158478	

Figure 11: Sample output file opened in Excel

Since the container has many uncovered openings the field keeps fluctuating inside the cryomodule due to the influence by earth's field. The error bars, black in color, shown on our plots are also very small showing that our measurements can be easily repeated. Comparing our results with the measurements taken at DESY (Deutsches Elektronen Synchrotron) (figure 13), the German Research center for particle Physics, for similar cryomodules, shows the consistency of our measurements. There are rises and falls in the field magnitude along the cryomodule with the least magnitude measured close to the center of the cryomodule just like in our measurements.

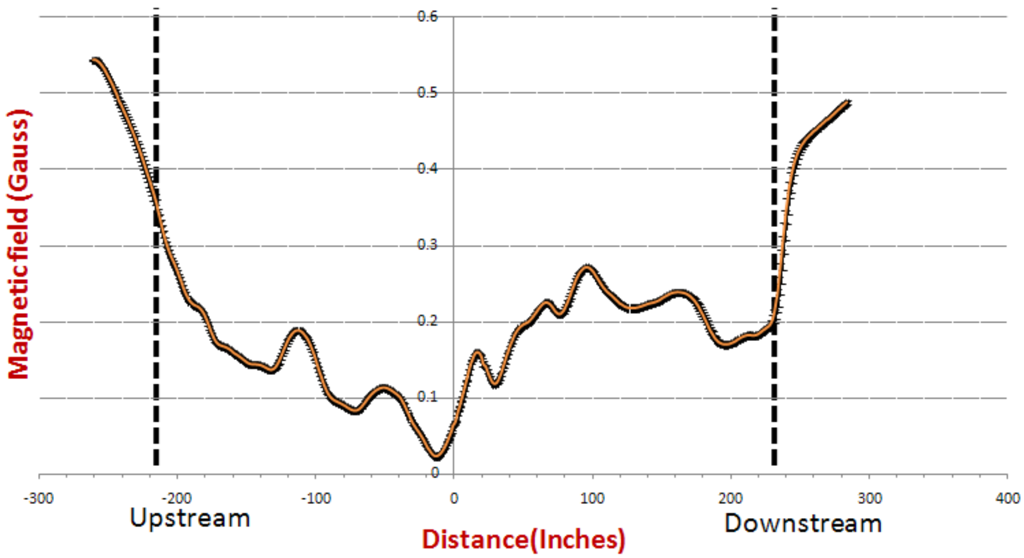


Figure 12: Magnitude of the field inside the Cryomodule. Field outside the Cryomodule is about 0.5G as expected, field decreases sharply inside the cryomodule to about an average of 0.1-0.2 G

4 Conclusion

We have been able to come up with a program that measures the field inside a cryomodule with minimal work. To measure the magnetic field one just needs to pull the magnetic sensor along the cryomodule while clicking on the Execute & Write button on the front panel of the program. The field measured is consistent with measurements done at DESY, the German Center for high energy Physics research. We measure the earth's field outside the cryomodule to be approximately 40-50uT while, because of the shielding, we measure a lower field magnitude of 10-20uT inside the cryomodule except at the points where there is an opening on the cryomodule and fields are affected by the earth's field.

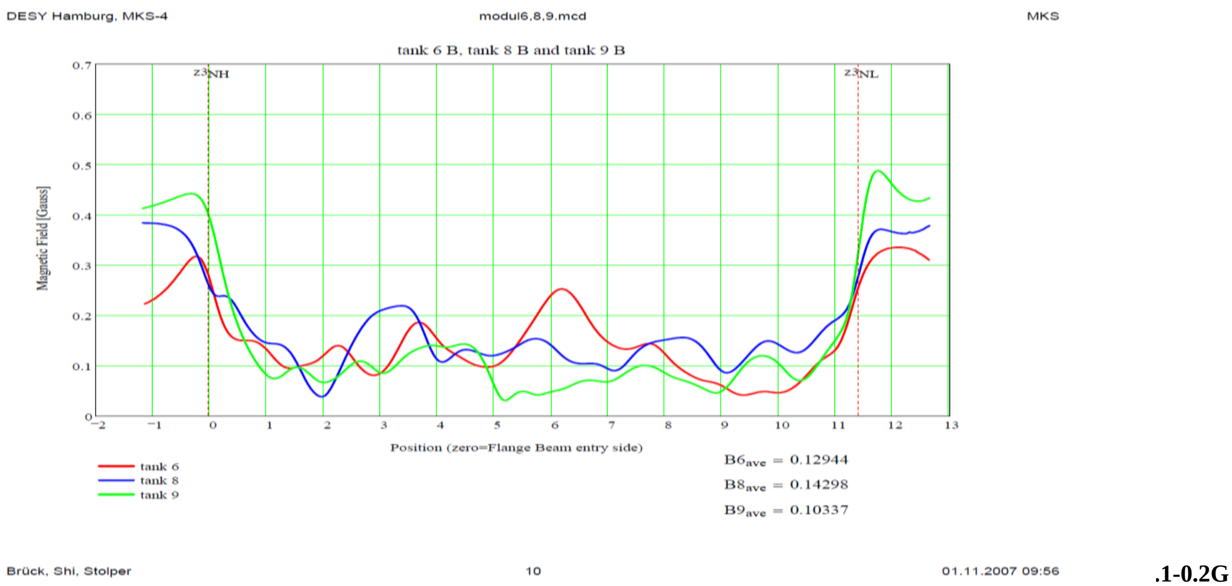


Figure 13: Field Magnitude Measurements done at DESY for different Cryomodules

5 Acknowledgements

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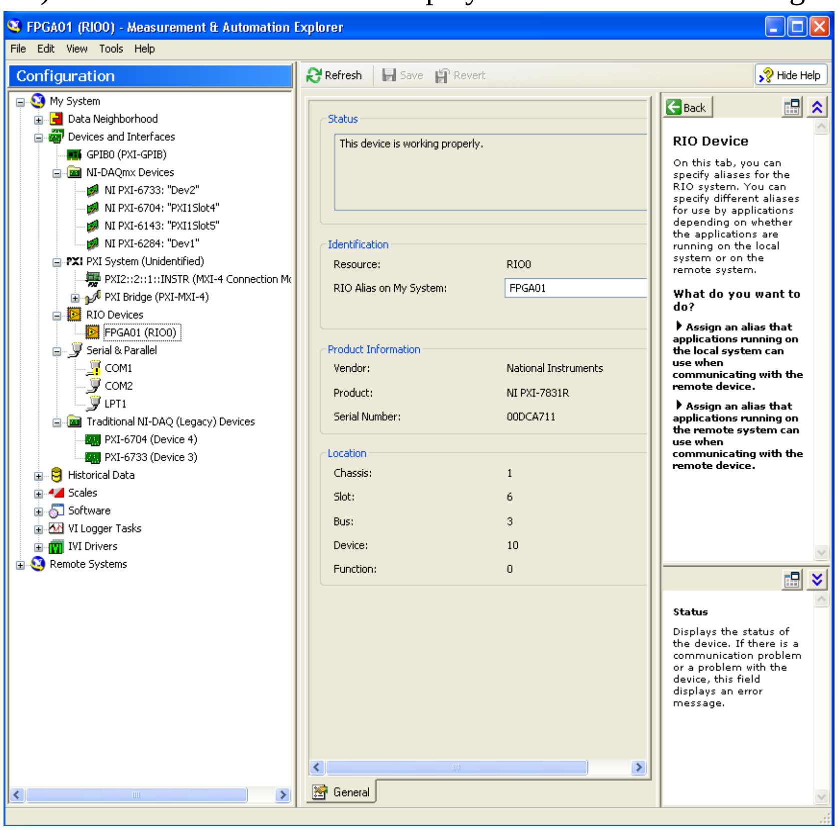
APPENDIX

Calibration of Instruments used in Superconducting and Conventional Magnets testing.

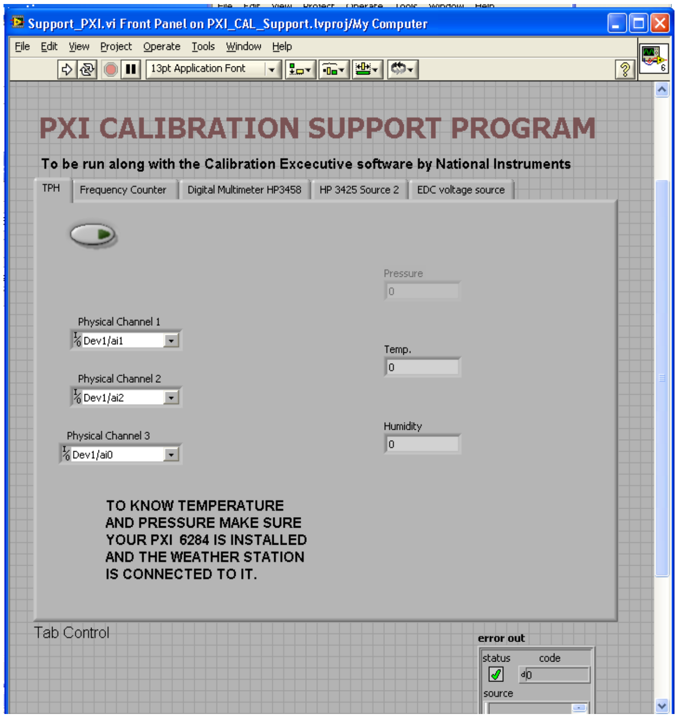
Calibration is the process of configuring an instrument so that it is able to produce readings/results within some accepted range. It minimizes measurement and output voltage errors. It is done to ensure that consumer satisfaction, accurate research findings and in compliance with the global standards of weights and measures. We calibrate instruments used for testing superconducting and conventional magnets. We work with digital voltmeters, voltage sources, frequency counters and function generators which are all controlled via a PXI crate and controller. The calibration programs are written in LabVIEW and are run on the PXI computer platform. In our calibrations, we set up instruments to be calibrated, run the test and calibrations, review the data and update the calibration database with results.

Calibration Procedure

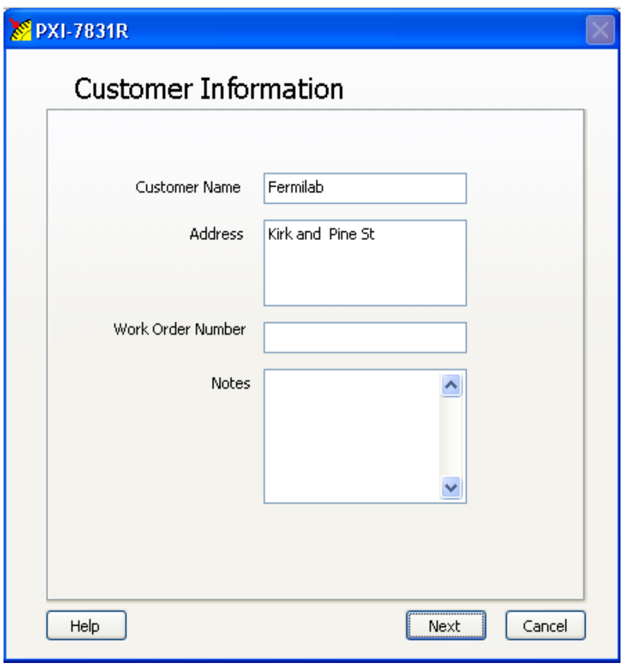
1. Open the calibration code written in LabVIEW which is located on the desktop (PXI_CAL_Support>>Support_PXI.vi).
2. Open the Calibration Executive and the Measurement and Automation software. On the Calibration Measurement and Automation window go to the left side bar and open the device you want to calibrate (this is where you get the device information such as the Serial number, device name and device number). The information will be displayed as shown in the dialog box below.



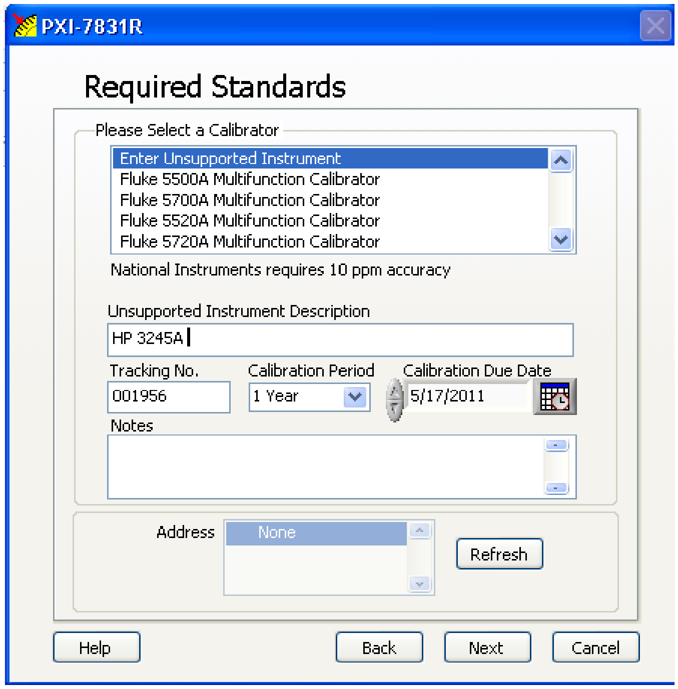
This is how the Support_PXI looks like



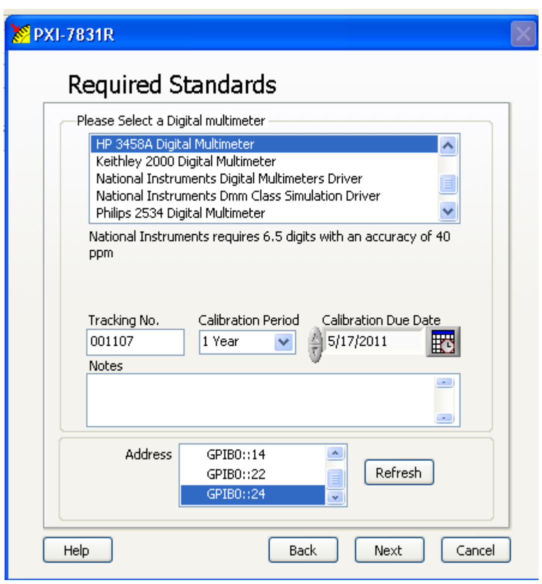
3. On Calibration Executive drop down menu select the device you want to calibrate then click on the calibrate button. Follow the procedure as prompted by the calibration executive. Enter the customer information



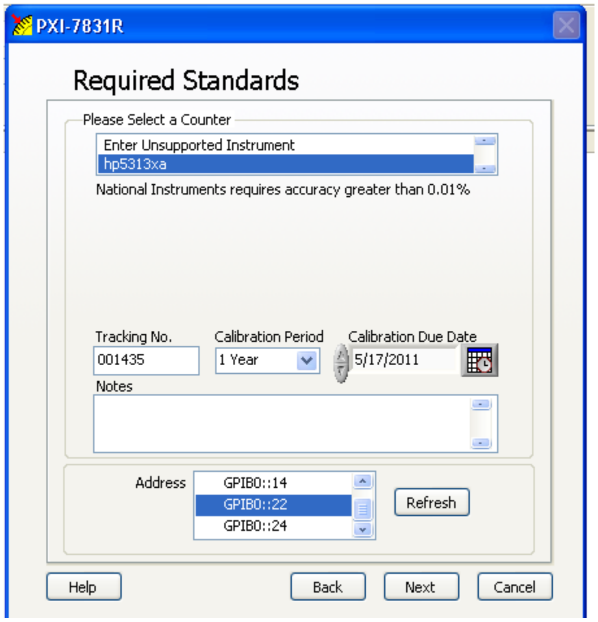
4. Select the calibrator from the drop down menu. We use HP 3245A or EDC 520, since neither of them is on the list, select Enter unsupported instrument and enter the missing information. You should be able to find the calibration due date and period (frequency) tag as well as the tracking number which begins with 00, on each of the instruments. The EDC520 calibrator works for higher voltages, while Hp 3245 only works for voltages between -10V and 10V. During our calibrations, we were however having some Technical problems with EDC 520, it couldn't output zero DC voltages.



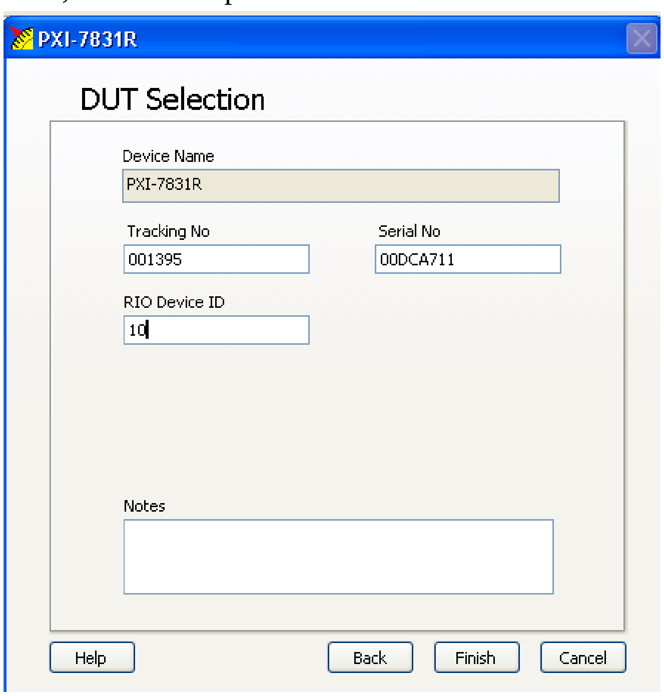
We use HP 3258A digital multimeter. Enter the information as shown below. Note the GPIB0 address is 24.



We use HP 53132 counter, whose GPIB0 address is 22.

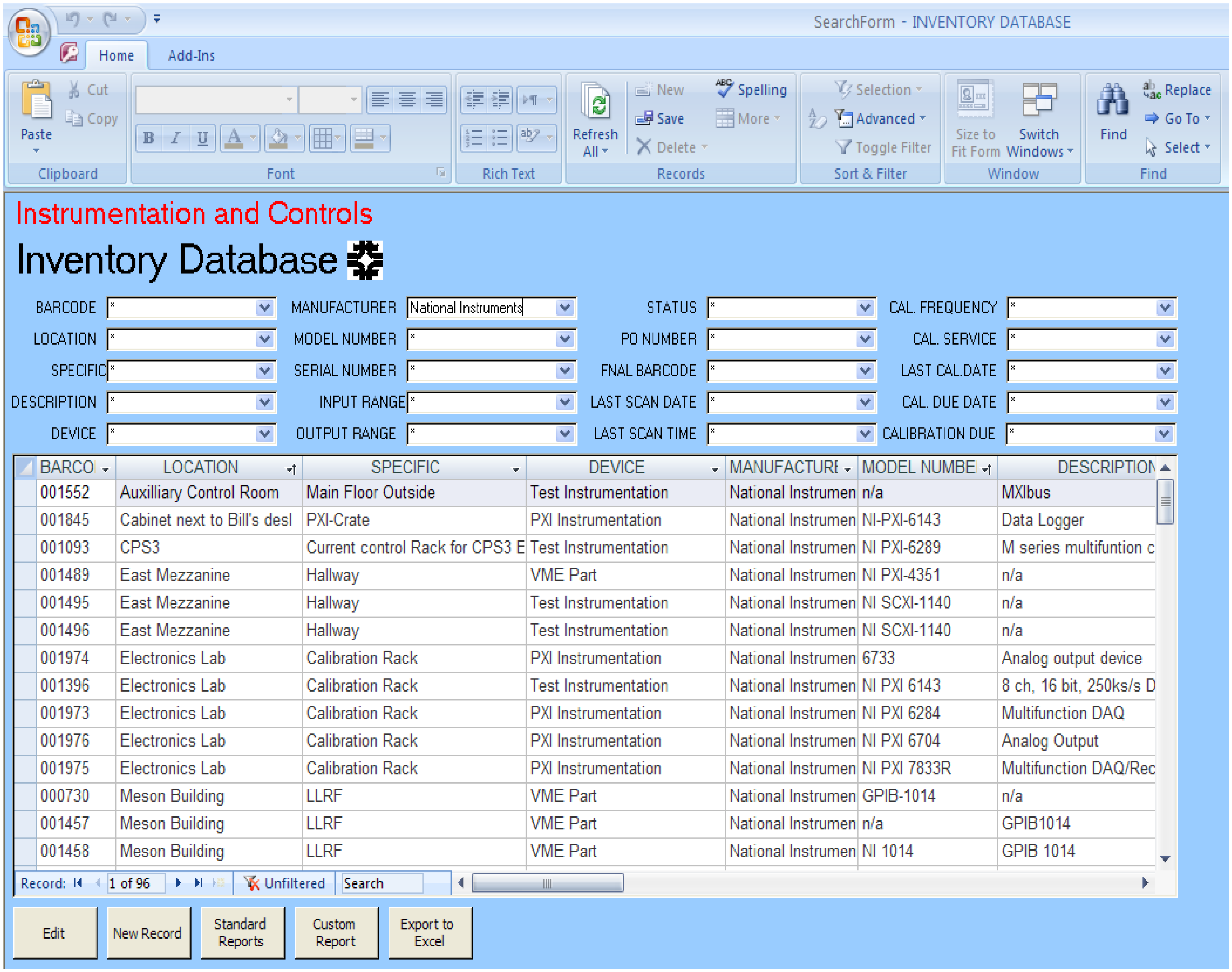


5. The next window that pops up is for the environmental conditions. You will need to measure this using the Support_PXI.vi. We have a weather station hooked up to the calibration cart which measures temperature, pressure and humidity. To get the readings, which you could do directly from the weather station, click on the TPH bar on the support_PXI.vi. Make sure the Boolean button is selected (turns light green when selected) then run the module. Fill in the temperature and humidity readings on the Calibration executive dialog box. Make sure you unselect the button in TPF before you exit.
6. Next, we need to provide information of the device to be calibrated. For this case, I am calibrating PXI-



7831R. Fill in the required information which you should have gotten from the Measurement and Automation window as described above. Then click finish and the Calibration should start automatically.

7. During the calibration procedure the program will ask you to output voltages and currents from your calibrator and when the verification and testing is done, the program will produce a calibration certificate which you will need to file with the other calibration documents in the calibration folder and update the calibration database on the S drive with the current calibration information. The picture below shows a page of the calibration database



Printed Circuit Boards Design using Altium Designer

Printed Circuit Board (PCB)

A printed circuit board, or PCB, is a component made of one or more layers of insulating material with electrical conductors [1]. It is used to mechanically support and electrically connect electronic components using conductive pathways, tracks or signal traces etched from copper sheets laminated onto a non-conductive *substrate* [2].

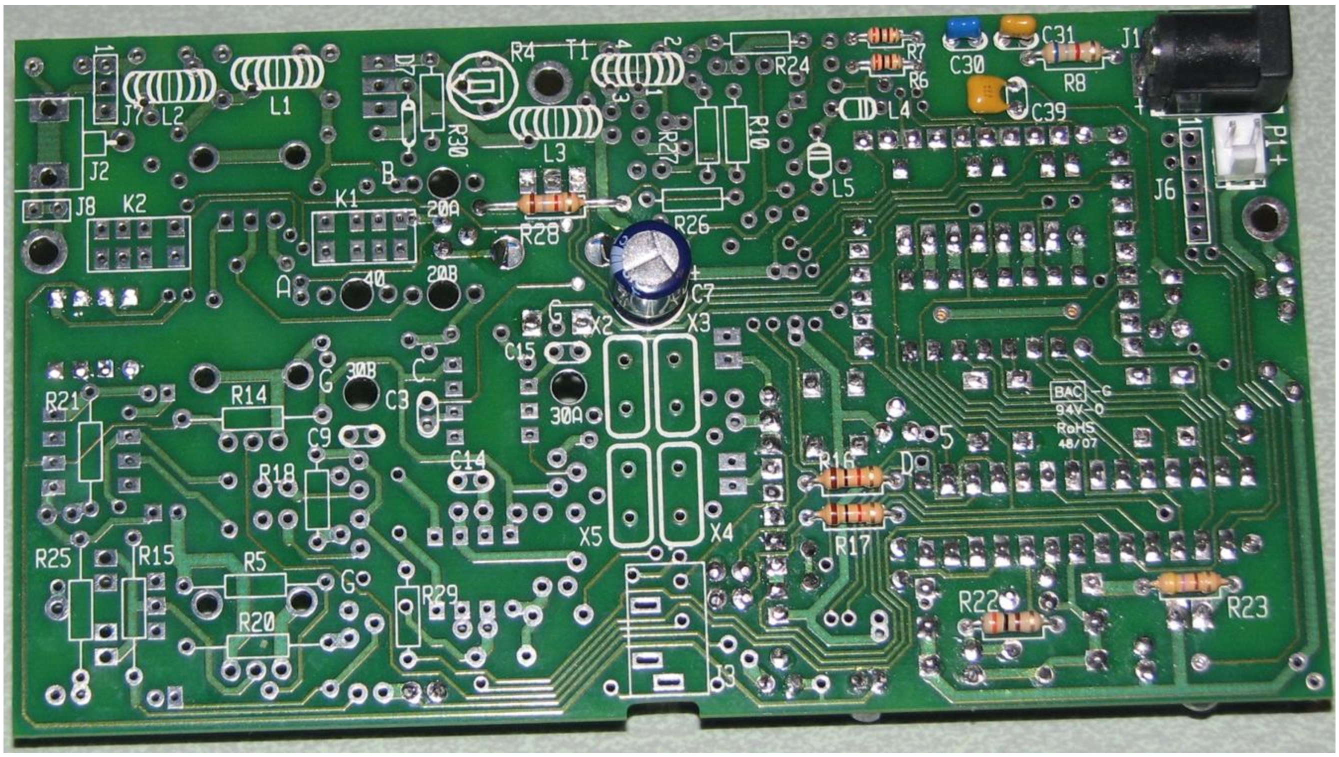


Figure 3: Printed Circuit Board

Altium Designer

Altium Designer provides a unified electronic product development environment, catering for all aspects of the electronic development process, including Front-end design and capture, Physical PCB design, FPGA hardware design, FPGA system implementation and debugging (when working with a suitable FPGA development board, such as an Altium NanoBoard), Embedded software development, Mixed-signal circuit simulation, Signal integrity analysis and PCB manufacturing. It includes all the editors and software engines needed to perform all aspects of the electronic product development process. All document editing, compiling and processing is performed within the Altium Designer environment. The Altium Designer environment is fully customizable, allowing you to set up the workspace to suit the way you work.

Using Altium Designer, we created the schematic below (figure 17). We also created components which were not already in the library as well as their footprints.

Creating new Components

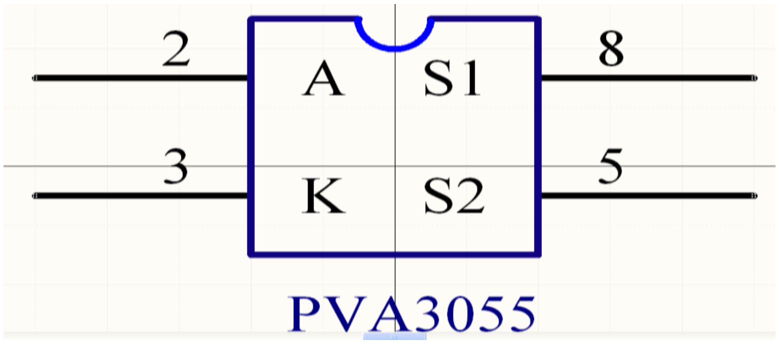


Figure 4: PVA 3055NS (photovoltaic relay) component symbol we drew to be used in the schematic

Creating Footprints

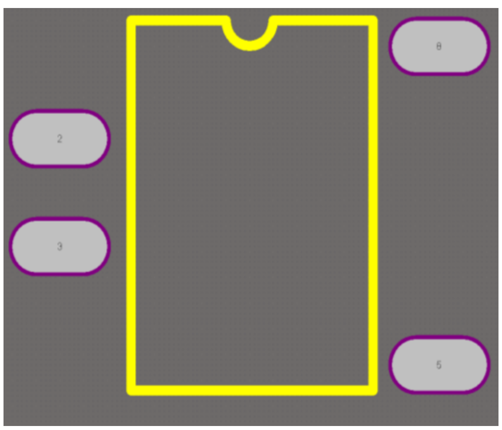


Figure 5: SMD Footprint we created for a PVA 3055NS (photovoltaic relay).

Procedures in the Design of Printed Circuit Boards

First you decide on the circuit that you want to create a Printed Circuit Board, you can sketch it with a pencil or have an idea in your mind and make a bread board version of it. Then you are ready to make a schematic drawing of it as shown in figure 17. A PCB design is a manufactured version of your schematic, so it is natural for the PCB design to be influenced by the original schematic. Convert the schematic to a PCB design, route it. Routing is the process of laying down tracks to connect components on your board. An electrical connection between two or more pads is known as a "net" [3].

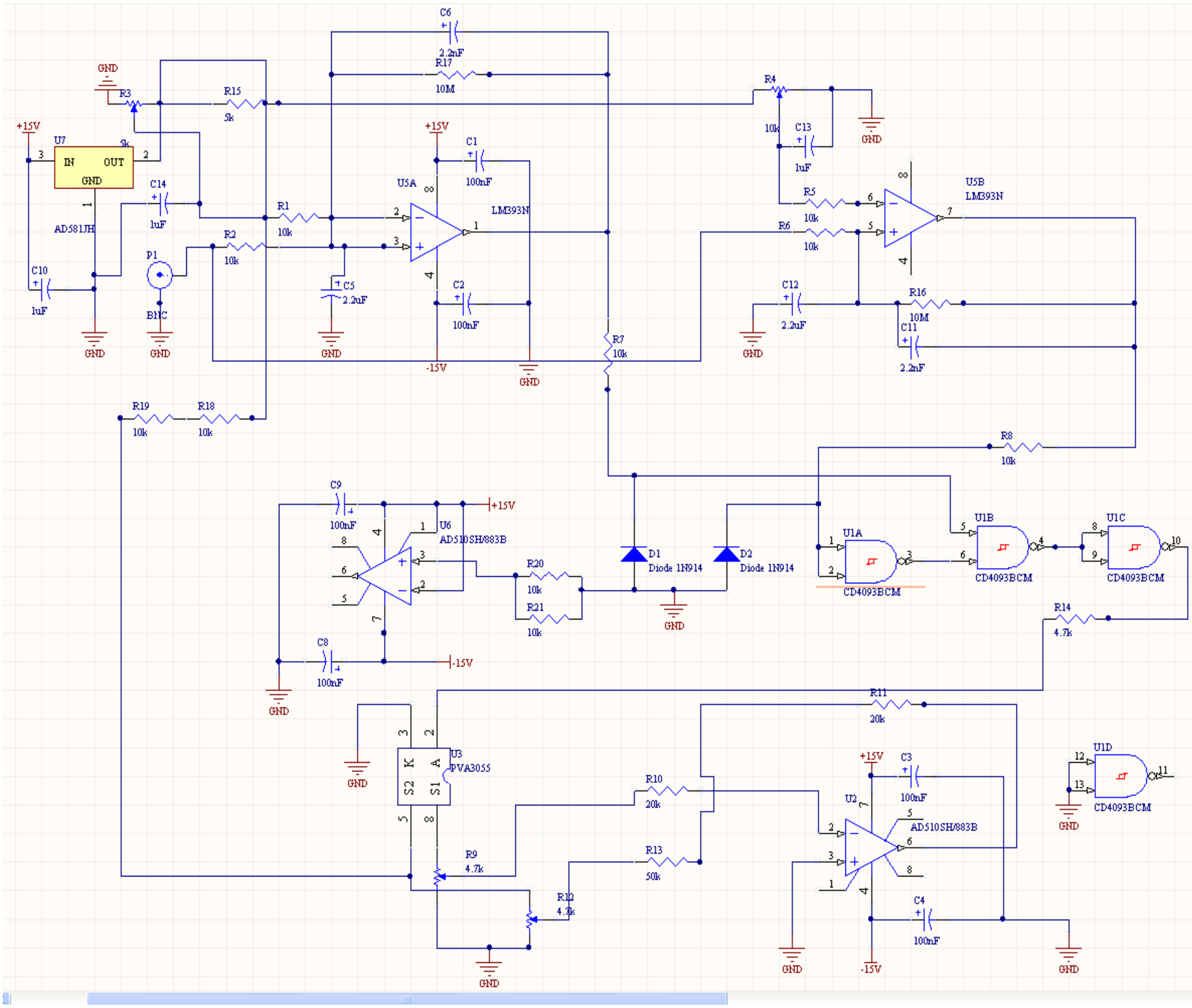


Figure 67: Circuit Schematic

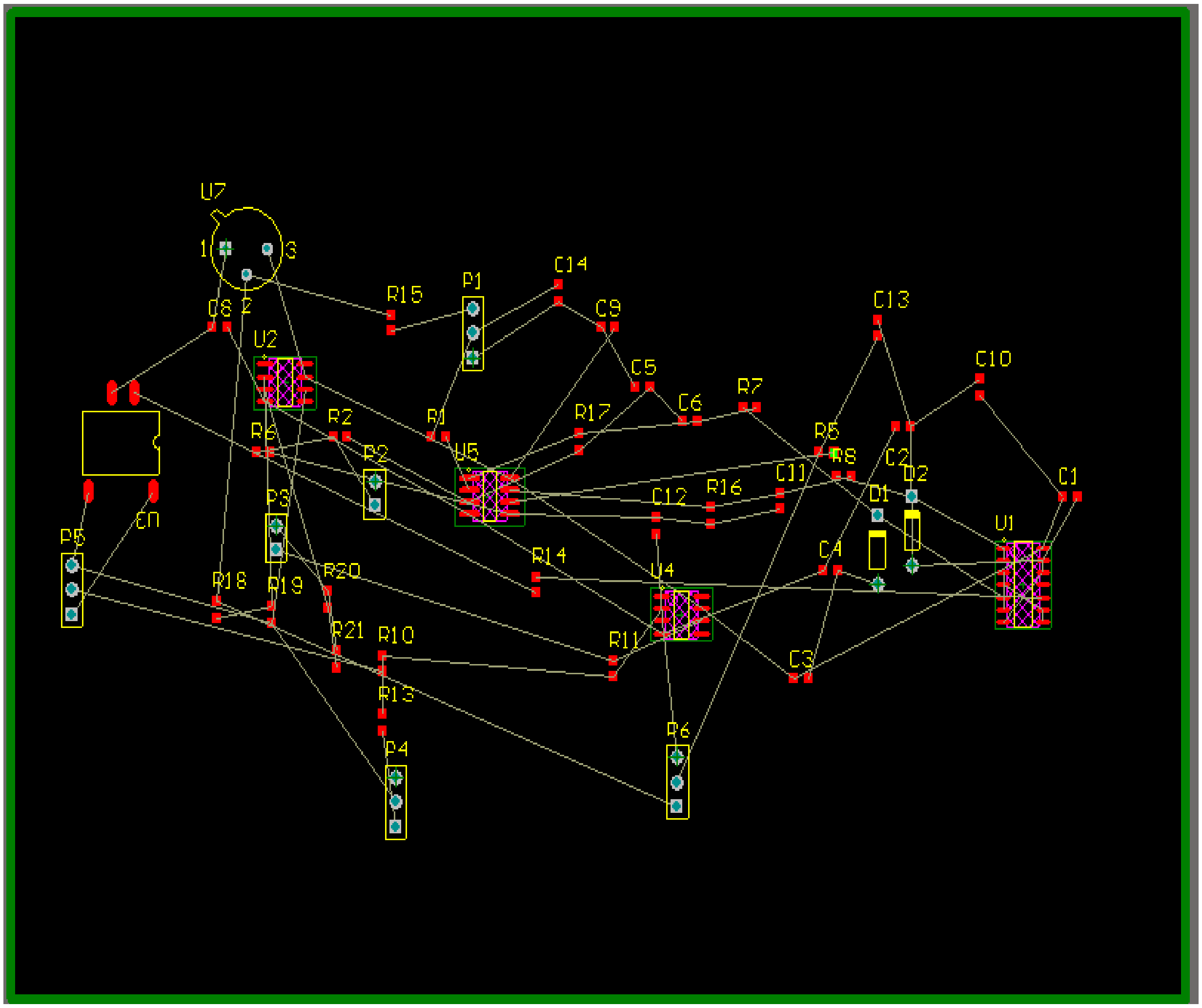


Figure 78: PCB layout

REFERENCES

1. Wikipedia < http://en.wikipedia.org/wiki/Printed_circuit_board>.
2. http://www.smps.us/pcb-design.html
3. http://www.alternatezone.com/electronics/files/PCBDesignTutorialRevA.pdf