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Programmable Control of the Stony Brook Tandem Van de Graaff

A Thesis Presented

by

Greg Wille

to

The Graduate School
in Partial Fulfillment of the
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in

Physics

(Scientific Instrumentation)

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Abstract of the Thesis

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The control system of the Tandem Van de Graaf (VDG) electrostatic accelerator was upgraded in situ, replacing analog control devices with digitally programmable devices, in order to make the control system more intuitive, automated, mobile, upgradable, and generally more user-friendly. The control replacement represents a change in mission focus from scientific research by a small number of highly skilled operators, to a new mission of education, outreach, and freelance precision measurement by a class of operators who are more numerous yet less highly trained. Design considerations and installation details are described within.

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1

Introduction

1.1 Extending the Lifetime of the Tandem VanDeGraaff

The Tandem VanDeGraaff(VDG) is an electrostatic linear accelerator which was popular in the mid 1900s. It is capable of producing continuous ion beams in the energy range of 5-80MeV which is now considered to be low to mid energy range. Similar models have been used to confirm the existence of many particles and states predicted by the standard model, and make excellent injectors for higher energy accelerators such as the Relativistic Heavy Ion Collider(RHIC) at Brookhaven National Laboratory(BNL). Today, however, their usefulness in experimental physics is dwindling due to the construction of new high energy colliders and the extent to which these energy ranges have been explored.

Nonetheless, the Tandem VDG at Stony Brook remains a valuable instrument which should not be forgotten. Since this accelerator is located on a NY State University campus, it is only fitting that it continue its service to the scientific community through the education of the next generation of future scientists. Like many historically significant experiments before it this means becoming part of the Instructional Lab. However, in its original state the accelerator would be too difficult to operate for students with no experience to perform experiments in a reasonable amount of time. For this purpose it was proposed that a new computerized control interface be produced to simplify the operation of the facility, from the ion source to the target, in such a way to reinforce the purpose of the Instructional Laboratory, which is to confirm the theories presented in physics courses and providing very important exposure to modern experimental methods.

1.1.1 History of VDG

The Tandem VDG was purchased by the department of physics from the High Voltage Engineering Corporation in 1966 and came online in of 1968. It was used by the physics faculty at Stony Brook University to perform experiments in Gamma Ray Spectroscopy, Giant Dipole Resonance, Charged Particle Reactions, Nuclear moments and applications to Solid State and Atomic Physics, leading to hundreds of publications, and 74 PhD degrees. It was used as an

injector for the super conducting resonant linear accelerator at SBU to conduct important measurements of the unstable element Francium, confirming predictions from the Standard Model. After attracting \$1.3 Million from NY State Legislature and \$40.4 Million from the National Science Foundation (NSF) over 40 years, the research potential of the superconducting LINAC no longer justified its expense, and it was retired as of November 2006.

From then on the Tandem VDG machine remained unused due to its incapacity to reach energy levels required to probe new areas of physical interest. Despite its inadequacy as a modern research instrument, the Tandem VDG beamline remains to be a rich resource for education, capable of reproducing important historical nuclear physics experiments and introducing optics considerations relevant to modern high energy ion beam experiments. Furthermore, with minimal additions to the ion source, the facility has the potential to be a useful tool for Accelerator Mass Spectrometry (AMS).

1.1.2 CCLI Grant

Funding for further operation of the Tandem VDG facility was sought from the Course Curriculum and Laboratory Improvement Program (CCLI) and approved in 2010, under the condition that the laboratory would be used to develop new methods of laboratory instruction. To this end, under supervision of the laboratory director, Tom Hemmick, the facility now provides access to the accelerator by hosting accelerator school programs targeting high school students, K-12 teachers, and undergraduate students.

1.1.3 Automation

The Tandem VDG is ideally suited for the Carbon 14 (^{14}C) dating technique known as Accelerator Mass Spectrometry (AMS), in which the particular charge and mass of the ^{14}C radioisotope is separated from the much more abundant Carbon 12 (^{12}C) and the amounts of each are compared to give an accurate measurement of an organism's age. More specifically, the amount of time which has passed since an organism ceased eating and breathing.

However, substantial automation is necessary for competition with commercial ^{14}C dating establishments, which handle many samples per day. This would not be feasible at the Stony Brook facility without the ability to automatically swap samples, quickly save and load tuning parameters, and monitor many feedback mechanisms.

The very minimum requirement in order to safely collect information about the relative quantity of different nuclear masses is the closed loop regulation of the

1. Inflection Magnet
2. Tandem Terminal Voltage
3. ^{12}C collection faraday cup position.

Of course, many other monitors and interlocks are highly pragmatic and any control structure must be expandable to incorporate such devices and future additions to the system.

2

Project Goals

2.1 Complete Conversion to Digital Control

There are many devices along the beamline monitoring and tuning the beam as it travels down the pipe. The beamline stretches a long distance and spans two rooms. This means that any control system will either need to send remote programming signals along hundreds of feet of wires, being distorted and attenuated along the way, or establish ‘nodes’ closer to the devices, distributed in positions which serve devices in a smaller radius.

Present technology makes transitioning from the former to the latter possible and adding a number of other attractive possibilities. The goal of this project is to replace potentiometers with digital to analog converters(DAC) in order to bring the advantages of microprocessors and the internet to the venerable Tandem Van de Graaff at the Stony Brook University Nuclear Structure Laboratory(NSL).

2.1.1 Voltage Controlled Remote Programming

A large number of instruments in the lab are remotely programmed through voltage programming generally in the range of 0-5V programming voltage corresponding to minimum to maximum scale output. In some cases the power supplies need a different range, particular termination, and/or bipolar input. The digital control system must be able to meet all of these requirements.

A solution to this requirement was found from the example of PRIME lab at Perdue University. PRIME employed National Instruments Multi-Purpose Data Acquisition(DAQ) modules, in the form of PCI expansion cards for Windows PCs running LabVIEW software. The lesson we learned from PRIME is that as the system grows, additional devices may be introduced which require spare control channels which are not present if each node is tailored to the specific instruments it contacts. A better alternative is to make a general purpose ‘node’, with plenty of general purpose I/O with spares on hand to afford adaptability to the total system.

As a result, a modular design for a general purpose node was created, consisting of a common PC equipped with a pair of National Instruments DAQ cards, the PCI 6703 and 6013, which

together provide 16 channels each of 16bit Single Ended Analog input, output, and Digital I/O.

The analog channels provided by this configuration is enough to control and monitor most of the power supplies which drive the electrostatic and magnetic beam optics.

2.1.2 Alternative Remote Programming

Some instruments do not follow the trend of remote programming through analog voltage. Fortunately, none of the devices in the beamline are controlled by means of a 4-20mA programming current standard, which would be more difficult to reproduce with the particular choice of NI hardware.

Two important instruments that utilize alternative methods of remote programming are the Inflection Magnet and the Analyzing Magnet, located before and after the Tandem VdG. Both of these magnets provide isotope selection by bending the trajectory of the portion of the beam with the desired mass-to-energy ratio by 90 degrees. Since each ion in the beam should have similar energy, this equates to selection of a particular mass. These two large bending magnets are controlled in two different ways, which are both unique to any instrument along the beamline.

The Inflection Magnet power supply and the Analyzing Magnet power supply are remotely controlled by a TTL standard frequency signal, and a RS-232 serial communication standard, respectively. Both of these two examples were addressed with relative ease due to the adaptability of the LabVIEW environment and the high level of compatibility of the ‘node’ design.

2.1.3 The Generating Voltmeter

As mentioned previously, the Analyzing Magnet relies on precise beam energy to steer the beam in the proper direction. Most nuclear experiments make use of an intense enough beam that some of the beam current can be collected as the beam passes through a pair of conductive slits and used to measure the bending angle of the Analyzer Magnet. That information is easily used to regulate the accelerating potential within the Tandem. That method of regulation is referred to as “Beam Regulation” or “Slit regulation”.

However, an alternative method for measuring and regulating the accelerating potential is needed for getting the beam in the neighborhood of the correct energy in the first place and for experiments which require lower beam intensity. It is these applications for which the Generating Voltmeter(GVM) exists. (2)

The GVM consists of several conductive plates, or “Stators”, which are arranged like slices of a pizza, facing the high voltage terminal of the Tandem, and a spinning conductive “Rotor” which shields half of the number of Stators at a time from the electric field of the terminal. As the Rotor spins, Stators are covered and uncovered. The GVM effectively chops the electric field experienced by the Stators, yielding an alternating current flowing between adjacent Stators, as an image charge is induced on the exposed area.

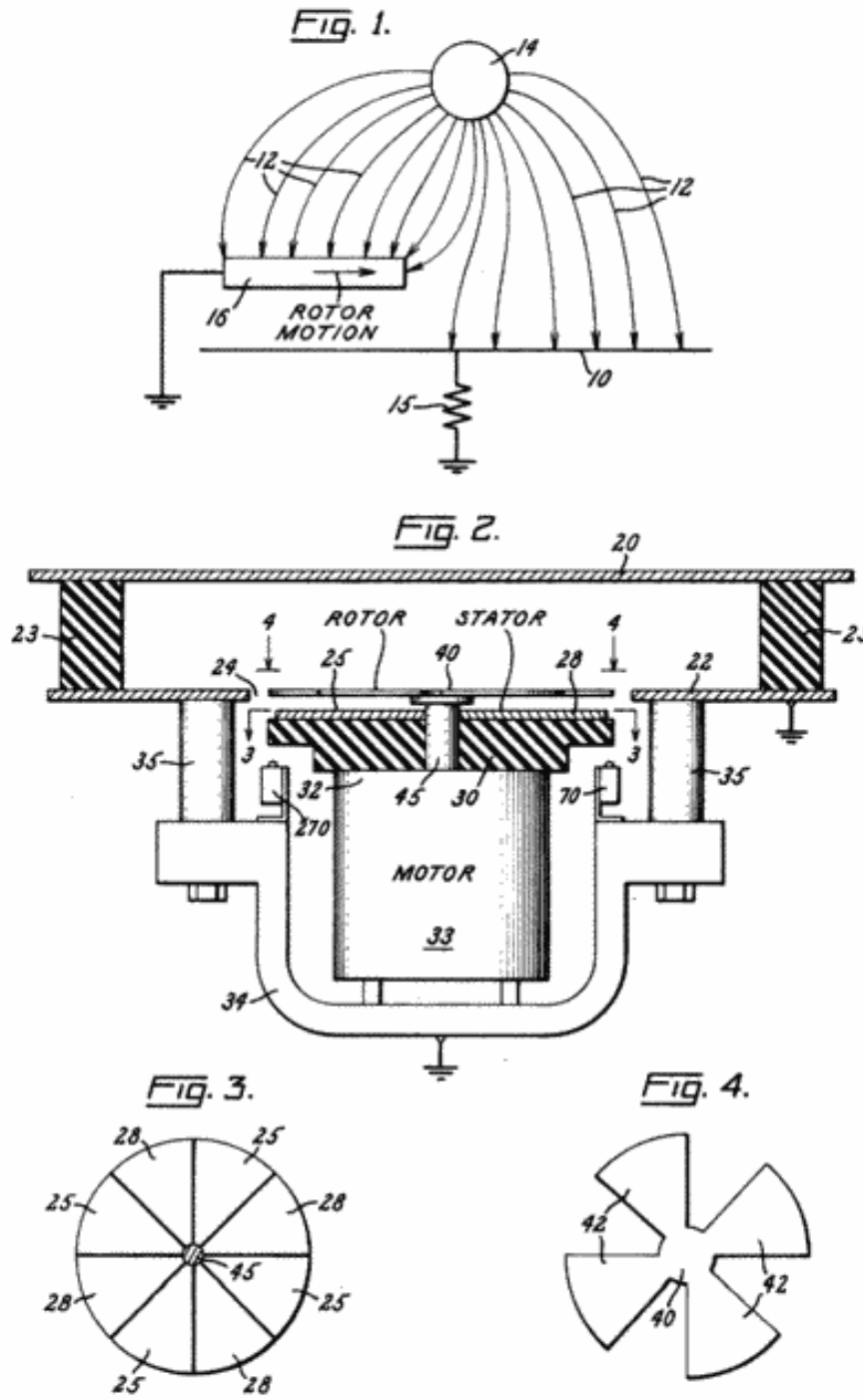


Figure 2.1: Generating Voltmeter Diagram from US Patent 4054835 (3)

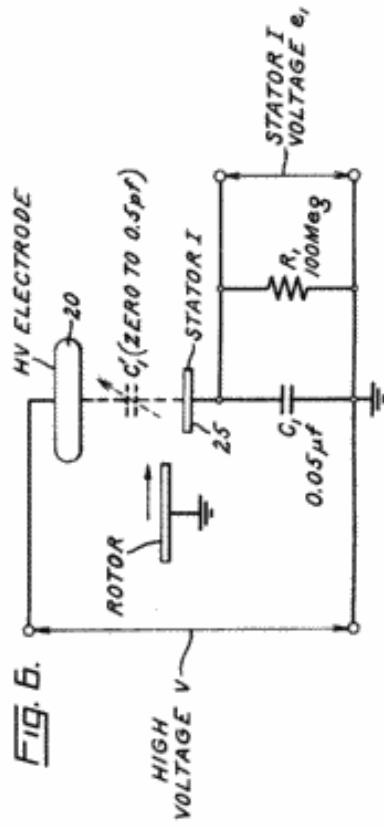
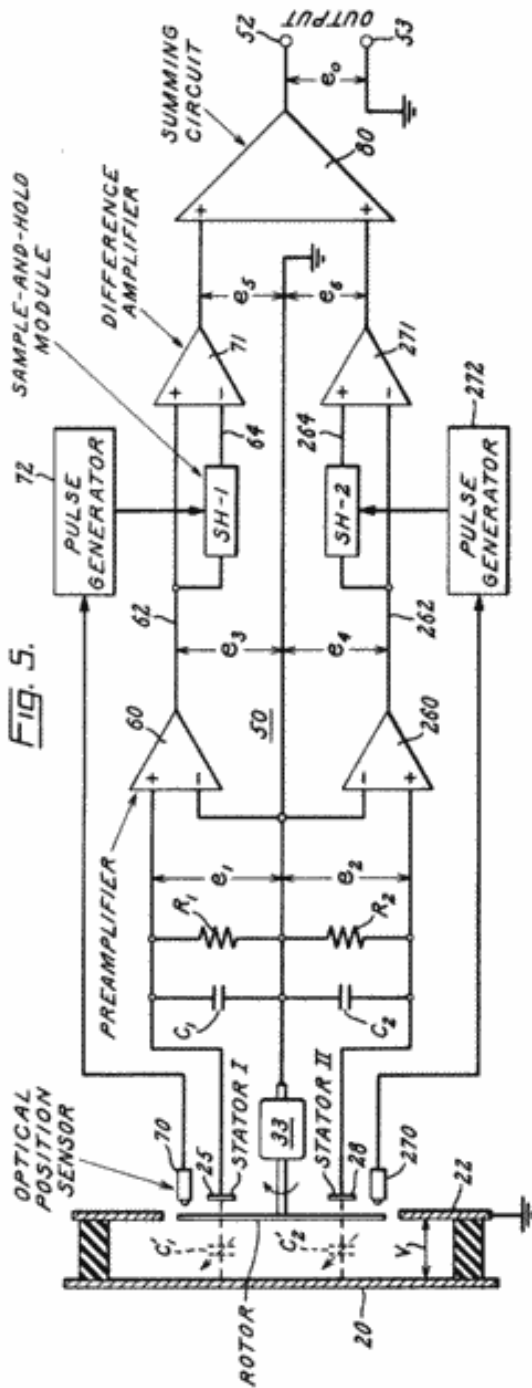


Figure 2.2: Generating Voltmeter Circuit Diagram from US Patent 4054835 (3)

In the past, this alternating current was rectified using vacuum tubes, producing a DC voltage level proportional to the Tandem Terminal Voltage. With the introduction of semiconductor amplifiers, an alternative to this method was suggested utilizing a “Sample and Hold” mechanism (see Fig. 2.2). Although this method was successful(3), it was proposed that the computational power of modern microprocessors might be better utilized by digitizing the unprocessed GVM waveform and applying a digital signal processing(DSP) technique.

As a result, a novel new approach was devised, modeled after the operation of the Lock-In Amplifier. This technique required a unique amplifier and software specifically designed for the task.

2.1.4 Beam Profile Monitor

The Beam Profile Monitor(BPM) gives an electrical signal which is a representation of the beam current as a function of horizontal and vertical coordinates in the plane normal to the beam propagation. It consists of a thin conductive wire which passed through the beam. The small current that this wire picks up is amplified and converted to a voltage signal.

The rate at which the wire is repeatedly passed through the beam is asynchronous and must be aligned in time by the use of a corresponding fiducial signal derived from a magnetic pickup.

2.1.5 Electrometer

The Electrometer is used to directly measure the beam current collected by the Faraday Cups. The Cup Current measurement is the most important measure of the quality of the beam, therefore it is the most crucial feedback to the user in the process of tuning the beam. The Cup Current will also be one of the measurements necessary for a successful Accelerator Mass Spectroscopy(AMS) analysis.

2.2 New Methods of Instruction

Hands on education is considered very effective and underutilized. One of the major goals of this project is to foster an educational environment which allows direct access to the accelerator facility to not only university students, but also the general public.

The proposed control system is designed to have a user interface with a graphical representation of each important beamline component so that the user may have an appreciation for each instrument they interact with, so that they may more easily understand the physics involved in the operation of those instruments.

2.2.1 Instructional Laboratory

University graduate and undergraduate students will now have the opportunity to perform nuclear physics experiments as one of three required instructional laboratories in the required courses of Senior Lab (PHY445) and Graduate Lab (PHY515).

2.2.2 Community outreach

In order to make the educational value of the facility even stronger, one goal of the project is to allow remote operation of the control system. For this reason, the capability of remote access via the internet is desired.

Remote access may allow high school classrooms perform nuclear experiments or accelerator mass spectroscopy on their own samples, encouraging interest in physics prior to enrollment in the University.

The system is also designed to make use of a standard windows compatible USB joystick or gamepad for tactile adjustments of tune parameters.

2.3 Accelerator Mass Spectroscopy

The primary prerequisite for the establishment of the Stony Brook Nuclear Structure Lab to become a competitive institution for the measurement of minute quantities of radioisotopes is the installation of the sample changing ion source. The system will need to be designed with expandability so that the necessary instruments to control the sample changing ion source may be added at a later date.

In addition to the capability of easy growth, AMS requires the system to be capable of automatic operation, so that many samples might be automatically measured logged, and the results made available promptly. The system must be capable of closed loop regulation of the Tandem Terminal Voltage through the GVM measurement, and capable of performing status and safety checks throughout the multi-stage operation of changing ion samples. For example, in the process of measuring the ratio of ^{14}C to ^{12}C in an organic sample to determine its age would require the system to load many saved tune parameters, wait for a period of time, check that the instruments have responded, confirm the instruments parameters within a specified range, change the Faraday Cup position, and sound an alarm if any interlock is tripped.

3

Architecture

3.1 Overview

The Tandem Computerized Control System is designed to be portable, modular, and expandable. It consists of a network of PCs in constant communication that coordinates the operation of all of the power supplies responsible for production and stabilization of the ion beam. PCs attached to this network fall into one of two categories, referred to as Masters and Slaves. Masters are responsible for user interaction and Slaves, positioned along the beamline, are responsible for controlling nearby power supplies through one of multiple protocols. A Slave PC is physically connected to each power supply it drives and will not be mobile. The Master PC is connected only through the Ethernet network and can be positioned in any location which is convenient. Typically only one Master is present on the network at a time.

3.2 Interface

The core of the control system is the user interface. The ultimate goal of this project is that a user should be able to configure all of the parameters of the beamline from one location. The interface organizes each of the power supplies according to which element of the beamline it influences, such as the Cathode Voltage or Bending Magnet Current. These parameters are overlaid onto a graphical representation of the beamline itself so that the user may more easily understand what effect each parameter will have on the beam. This organization also guides the user from one beamline element to the next during the process of tuning the beam.

Once a beam tune has been established it can be saved to a file and reloaded at a later time. This enables another option that will be utilized in the future, in which several tunes will be cycled continuously in a loop for many different source samples. During such an operation it is not necessary that the GUI software be running at all, replaced by another piece of software which will step through a prescribed profile of tuning parameters, and checking compliance of the attached devices through various feedback channels and interlocks before moving on.

3.3 Slave PC

The Slave's performance is the most important factor in the success of the new control system. Slaves are responsible for setting the analog programming voltage signal applied to each power supply, and limiting the ramp rate of those signals. This is important due to the nature of the optical elements which are driven by the power supply, which may represent a capacitive or inductive load. Failure to properly limit this rate may cause damage to the power supplies or beamline elements or may cause error conditions on the power supplies which must be cleared manually. It is also imperative that Slave PCs operate independently from one another and are capable of stable operation during periods of time in which the communication with the Master PC is lost.

Slave PCs are composed of interchangeable parts, so that a minimum number of spare parts are required to be prepared for a part failure. Thus, each slave is designed to be able to drive any instrument that exists in the system. The software which runs on each slave is also designed to be as similar as possible, making it easy to add new instruments, new slaves, or reconfigure the laboratory layout.

3.3.1 Slave Hardware Considerations

The Nuclear Structure Lab represents an unusually harsh environment for the components of the control system. Several components of the control system must be electrically isolated from laboratory ground potential but still maintain network communication, the possibility of power surges, high voltage electromagnetic induction(EMI), power outages, and water leakage exists. Therefore a large emphasis is placed on protection of hardware and robust, replaceable parts.

3.3.2 Slave Software

Since it is expected that additional Slave PCs and instruments will be added to the system, the software architecture must be designed with room for growth. Slave software is designed to be general enough that a new Slave PC may be added to the system and installed with a template version of the software and made operable with very little configuration. Data concerning individual power supply parameters such as the correspondence of each power supplies output to its applied programming voltage must be stored in another location. Therefore, in addition to the GUI software, which accepts user commands and relays them to the Slaves, and the Slaves themselves, which condition those commands and applies them to the instruments, another structure must exist which is essentially a database containing each instrument's specific calibration information.

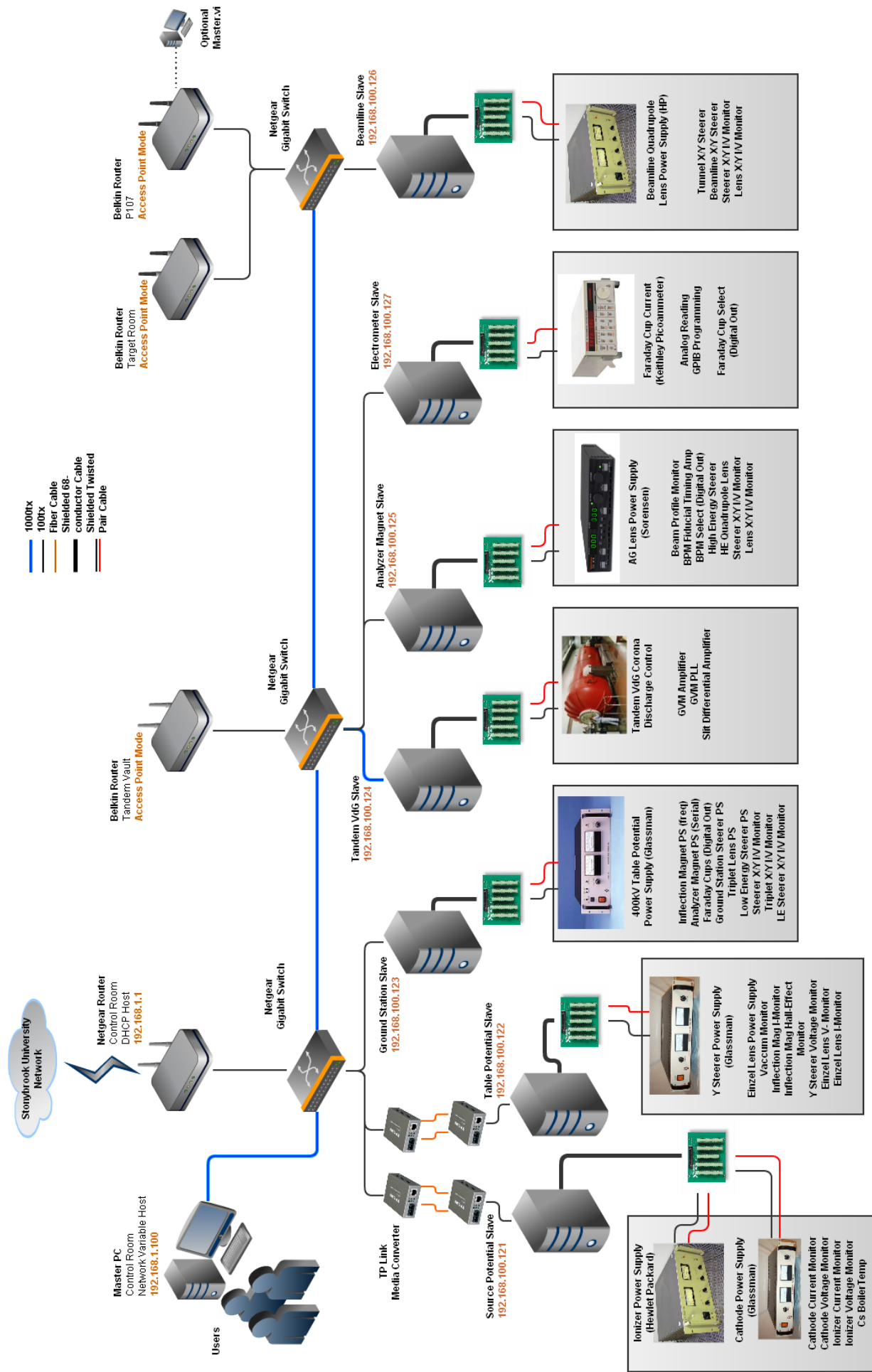


Figure 3.1: Diagram of control system architecture.

4

Implementation

4.1 Overview

The system currently consists of eight identical PCs in communication with each other over a private LAN. As stated previously, the roles of these PCs fall into two categories, referred to as Slaves and Masters. Slave PCs are named for their function, which is to carry out commands sent from a remote location. They are installed with the LabVIEW RealTime(RT) operating system which is extraordinarily suited for that purpose. Utilizing LabVIEW's extensive supply of instrument specific drivers, multipurpose I/O, and protocol compatibility, the Slaves are able to manage multiple power supplies and other instruments simultaneously. The single PC intended for human interaction, known as the Master PC, handles all of the network traffic with the slaves and is responsible for hosting the Graphical User Interface. This PC runs Windows XP and may access the Internet through the University's network.

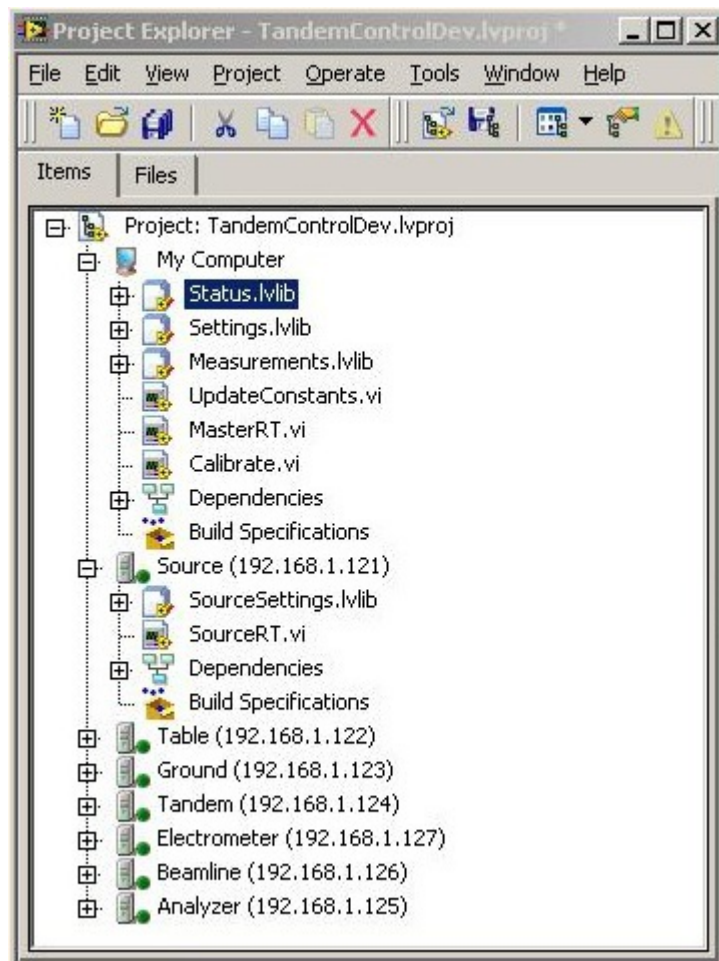
Communication between the LabVIEW Virtual Instruments (VIs) running on the Master and the Slave PCs is accomplished through the National Instruments Shared Variable Engine (NI SVE). The Master PC acts as a server, hosting Network Shared Variables (NSV) which are accessed by all of the VIs belonging to the project. These Shared Variables serve different purposes. Some are for organization, containing information that determines which setting gets routed to which device, some variables contain device calibration information and setpoints, and other variables are for bookkeeping and monitoring error status.

4.1.1 Project

The system is totally embodied by the LabVIEW Project file, which is the highest order in the hierarchy of LabVIEW structures, the parent of all other objects. The Project file contains all of the VIs which run on the Slave PCs and the Master, and also all libraries, which are structures that allow the definition of Network Variables. All Network Shared Variable information is defined within the project, which allows VIs running on different machines to access shared memory over the network. The Project is also instrumental in programming networked PCs installed with LabVIEW RT, referred to as RT Targets within the LabVIEW Documentation.

Figure 4.1:

The LabVIEW Project Explorer shows the project in a tree view. The Master PC is listed first, labeled “My Computer”. The Slave PCs are also shown, labeled by their names and IP addresses. In this example, the Slave PC named Source is expanded to show its library and VI.



4.1.2 Internal LAN

To provide communication between each element of the system without taxing the University networking hardware, a gigabit ethernet backbone follows the beamline from source to target. It consists of three Netgear GS108T hardware switches in a daisy chain configuration. (Switches provide more intelligent network traffic management than network Hubs but require less maintenance than Routers which also include several additional features, unnecessary for this application.) Each Slave PC is identified by its static IP address. The use of static IPs ensures that a Slave can not accidentally be loaded with the incorrect VI.

4.2 Master PC

The Master PC has two distinct roles. It hosts all of the Network Shared Variables that are accessed by the Slave PCs, and it typically runs the main user interface VI called Master.vi. The distinction between these two roles is that the Shared Variables are defined by the Project file, which distinguishes the Master PC as the network location where those variables may be accessed, as opposed to the Master.vi, which may be run on any windows PC connected to the internal LAN.

The Master PC is installed with Windows XP, National Instruments LabVIEW 8.6, National Instruments DAQmx 8.9, and the LabVIEW Real-Time module.

4.2.1 Shared Variable Libraries

Libraries can be used to organize many filetypes withing the LabVIEW development environment. For this project, however, they are simply used to define Network Shared Variables that will be accessed by networked PCs. These variables are used to map the parameters required to interface properly with each specific instrument to the correct output channel on the correct Slave PC.

Except for certain exceptions, each Shared Variable is set up as an array of data type String, 32-bit Float, or Boolean. The n th element of each array corresponds a particular hardware channel on a particular Slave PC, and each Slave PC is responsible for 20 elements. Any time that a Slave PC is added to the system, the parameters of the devices with which is it intended to interface must be appended to these arrays in the correct index, corresponding to the physical channel on the Slave PC.

- Measurements.lvlib

Defines all Network Shared Variables pertinent to measurements made by the Slave PCs. (see Fig. 4.2a) The first is an array of every measured value from all of the slaves. It is not actually used except for bookkeeping purposes. The next five are characteristics of the individual measurements collected by the Slave PCs, most importantly the units and linear calibration coefficients m (slope) and b (offset).

Each Slave has a corresponding Shared Variable which is an array of 20 Float elements and is labeled by the name of the Slave and its starting and ending index. They are separate from each other so that the Slave PCs can each write data into their own variable without interference. These arrays are concatenated to produce the full length array of all measurements. Any Slave PCs added to the system must have a corresponding array variable inserted into this library.

Slave PCs also have Digital I/O available. In case these channels are configured as inputs, their values are included in the DigitalIn array.

BPM and NanoAmmeter will be addressed in Section 4.4

- Settings.lvlib

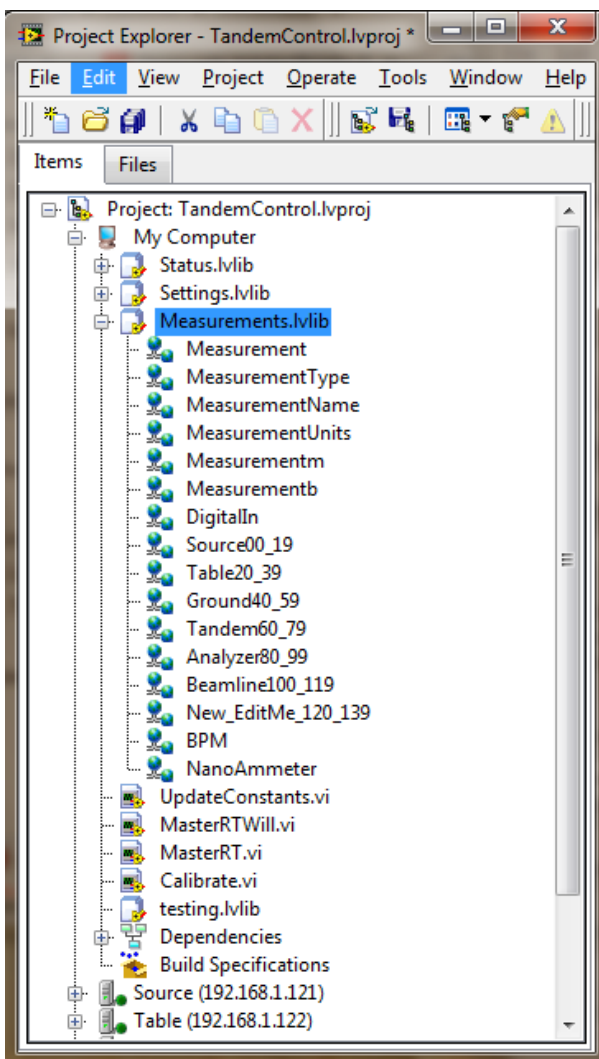
Defines all Network Shared Variables pertinent to the intended set points of the power supplies driven by the Slave PCs. (see Fig 4.2b) Again, the first variable is used for bookkeeping purposes, followed by similar calibration coefficients, units, types, and the setting name. Instruments are targeted in the GUI by searching the array of setting names for a matching string. The index of the array of names at which a match is found is the hardware channel of that device.

Additionally, the settings library includes parameters for protection purposes. Max, Min, and InstrumentRampRate define the limits of the power supplies and the maximum rate of change that can be tolerated by the corresponding power supply.

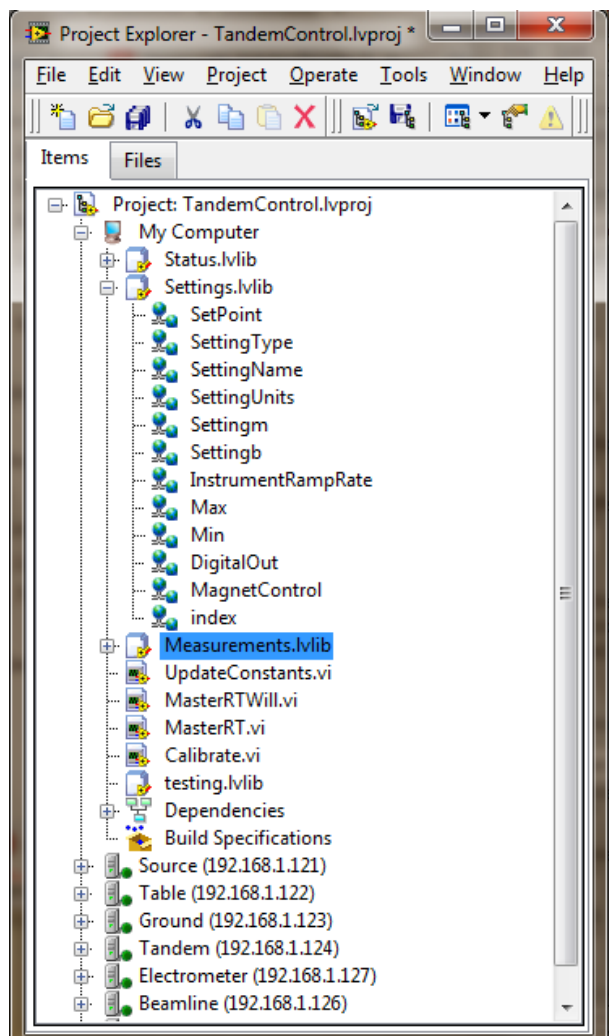
Digital outputs are also included in an array labeled DigitalOut.

- Status.lvlib

Each Slave VI collects several error status indicators and forwards them to the Master PC where they can be viewed on the Overview tab of the GUI. These indicators are useful in diagnosing any problems with PCI hardware or networking components.



(a) Measurements.lvlib



(b) Settings.lvlib

Figure 4.2: Network Shared Variables defined by libraries within the project. These variables are hosted on the Master PC and may be accessed by any VI which is also a member of the project via the NI Shared Variable Engine.

4.2.2 Master.vi

The Master VI is one of three Virtual Instruments intended to be used directly by the user. It can be run on any PC connected to the Internal Private LAN and can even be run simultaneously on multiple PCs in principle. Obviously it is not intended that multiple users should ever be actively tuning the beamline settings at the same time, in such a situation one user's actions would negate the other. However, when the VI is idle for over 30 seconds it will refresh its setpoints to reflect any changes that may have been made from an alternate source, maintaining consistency between the displays in the event that the user wishes to change location, or switch to an alternate control method such as an automated control or remote access.

The Master VI is able to Save and Load a list of setpoints which define a beam tune, allows the user to select which faraday cup current is being measured, control the position of each faraday cup in the beamline. It also displays the horizontal and vertical profile of the beam measured by the Beam Profile Monitor.

In the event that the user adjusts one of the set points, the Master VI immediately transmits the new setting to the Slave PC responsible for controlling the desired power supply. The Slave VI is responsible for unit conversion and rate limiting, so that its output is "bumpless".

- Overview Tab

This view displays a floor plan of the lab with the locations of each Slave PC marked with a green light indicator. This light is illuminated if the slave has all clear error status for its network variable access, as well as reading and writing to the PCI hardware through the DAQmx vis, and is in constant communication with the Master PC. The user may hover the mouse pointer over any of the Slave status indicators to view the full error status report as well as the time stamp of the last successful communication from the Slave PC.

- Ion Source Tab

The Ion Source Tab groups together all of the devices necessary to tune a beam for injection into the Tandem and displays their current values overlaid on top of a graphical representation of the physical Ion Source. Even though the power supplies shown on this tab are handled by several different Slave PCs, the user may remain ignorant of this fact, simply pointing and clicking on an optical element of the beamline and adjusting its desired value.

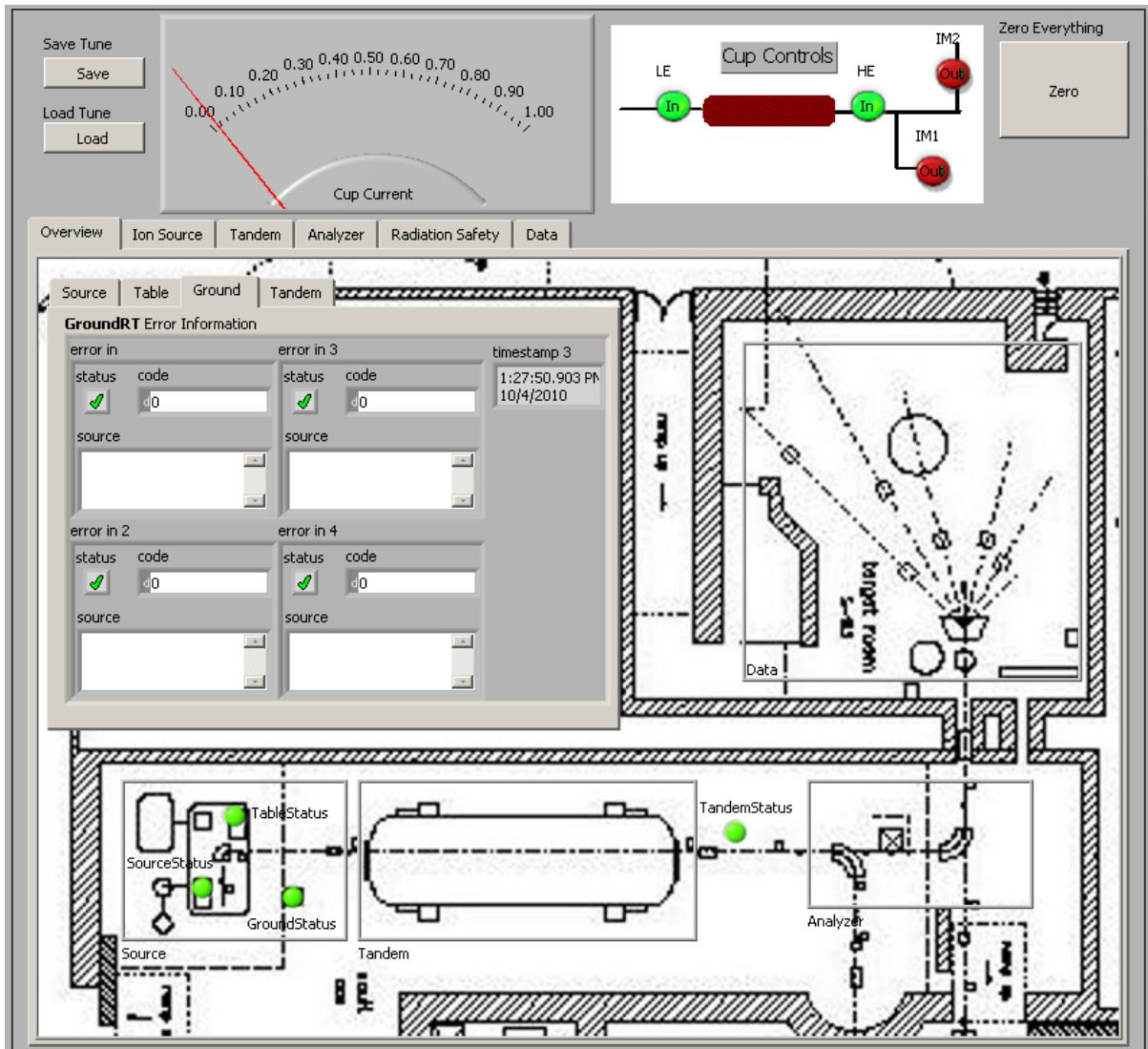
- Tandem Tab

Similar to the Ion Source Tab, the Tandem Tab displays a graphical representation of the beamline, this time centering its focus on the Tandem VanDeGraaff Accelerator. The instruments displayed on this tab are all related to the focus and steering of the beam as it passes through the Tandem to the Analyzing Magnet, with the Tandem Terminal Voltage and the Analyzing Magnet itself acting in unison as a steerer which guides the component of the beam with the correct Energy to Mass ratio through a 90° bend. From

this tab it is possible to select either “Slit” or “GVM” as the desired method of Terminal Voltage regulation.

- Beamline Tab

The final set of beamline optics before the target are displayed on this tab. These allow small adjustments to fine tune the beam to maximize beam current onto the target.

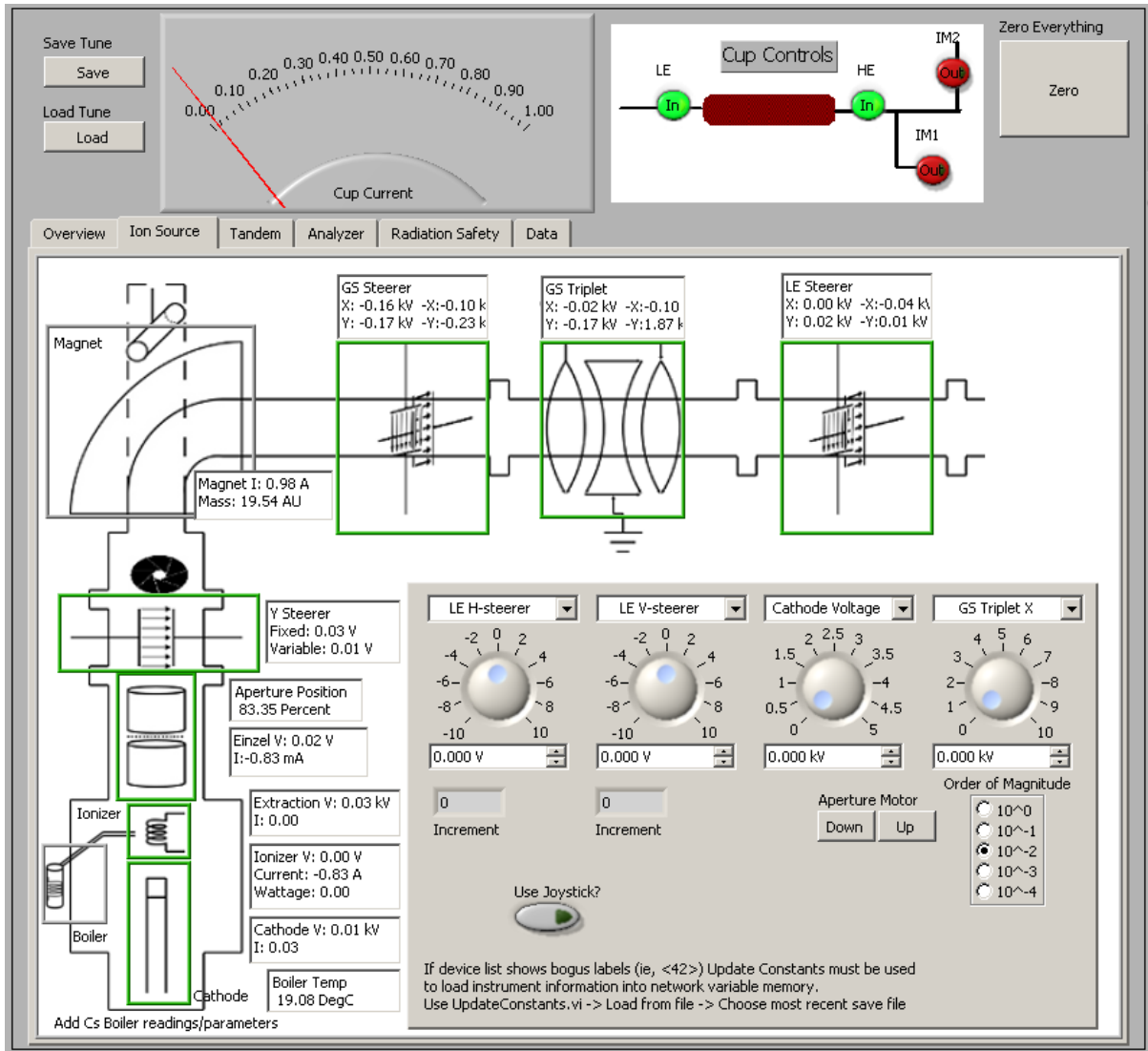


(a) The Overview tab displays the floor plan of the lab with the locations of the Slave PCs and each of their error status.

Figure 4.3

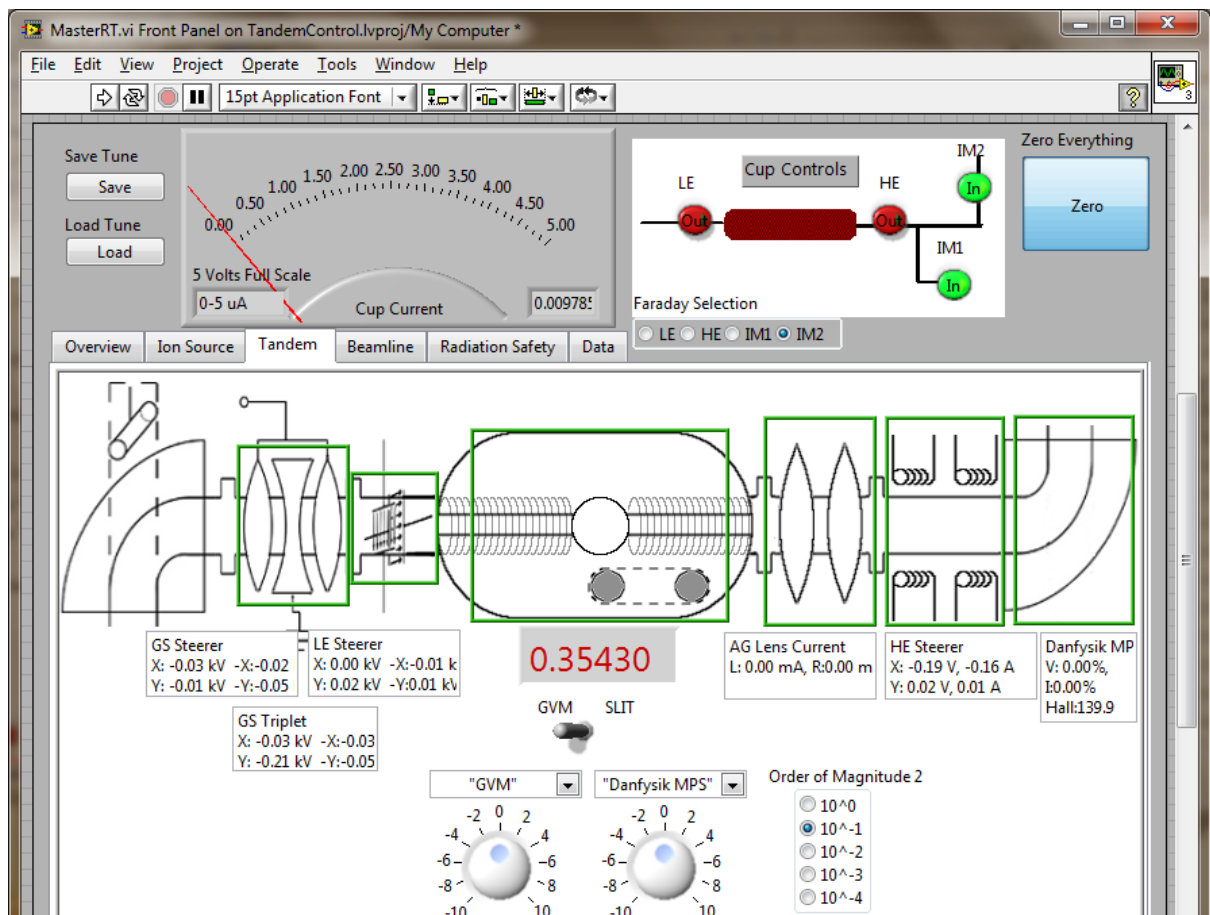
4.2.3 UpdateConstants.vi

Where Master.vi is designed to be an educational and time-saving tool for operating the facility, UpdateConstants.vi is intended for administrative purposes. This VI is like a switchboard, it is responsible for correlating each setpoint with the correct physical hardware channel amongst all of the Slave PCs. This is accomplished by filling the many Shared Variable arrays residing on



(b) The Ion Source Tab presents the user with a graphical representation of the physical Ion Source. The beamline elements can be chosen from a drop down menu or selected by clicking within the highlighted field. The selected instrument can be adjusted by simple numeric entry, clicking on the control knob, or through the use of a USB joystick or control pad.

Figure 4.3



(c) The Tandem Tab shows the optical elements before and after the Tandem VdG. From this screen the Terminal Voltage regulation method may be selected in addition to the tuning functions similar to the Ion Source Tab.

Figure 4.3: Master VI simplifies the process of tuning the beam by grouping related elements into smaller sections.

the Master PC with the information regarding which power supply or measurement is located at which hardware channel. Hence its name.

UpdateConstants.vi is the place to go to inform the system that a new device has been added and what are its operational parameters. Since the front panel display shows all of the arrays side by side as a spreadsheet, all that is needed is to fill in valid data into a row at the proper index. Since Master.vi locates each device by a string search through the array of names at start up, a newly added device will immediately be available from the pull-down menu on the GUI. However any permanent additions will require editing of the Master.vi. (An effort has been made to simplify the task of adding buttons and indicators for this purpose.)

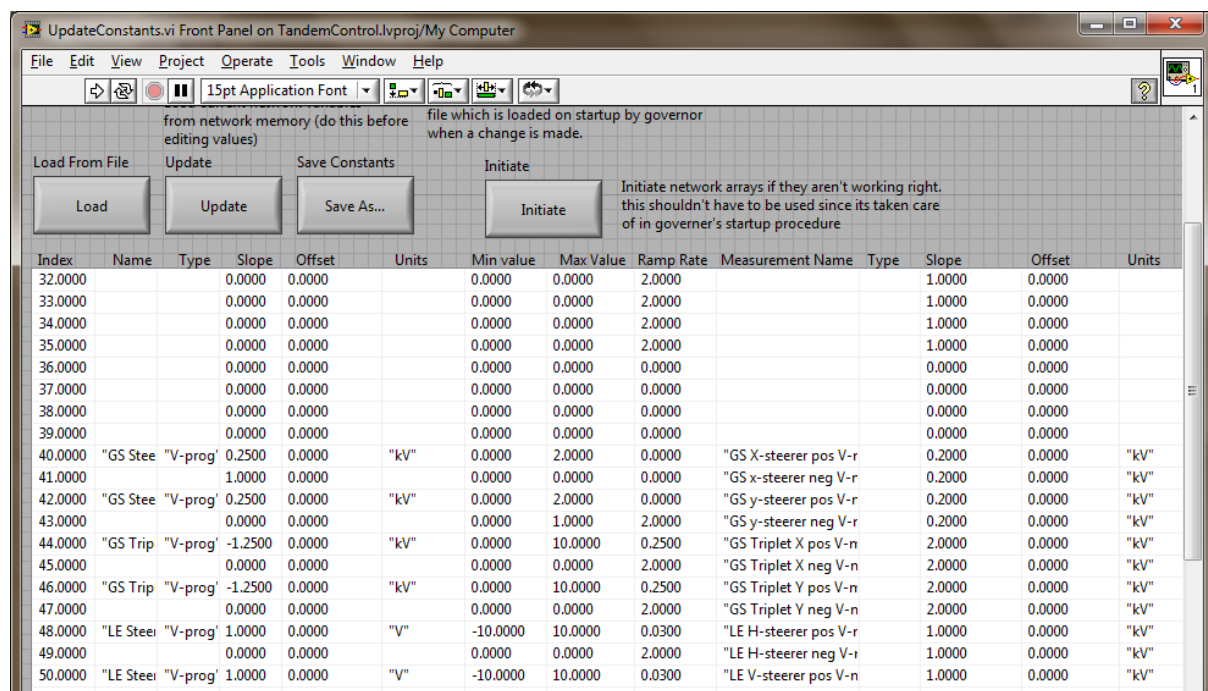


Figure 4.4: UpdateConstants

4.2.4 Calibrate.vi

This simple VI is a tool to help calibrate between the programming/monitor signal, which is usually a DC voltage, and the actual power supply output. The calibration procedure requires the operator to set the software setpoint to two different values and note the device's response with a reliable method of measurement. The VI then calculates a linear approximation of the power supply's response and updates the parameters for that device. This VI may be used to calibrate settings and measurements, it can be run on any windows PC attached to the internal LAN. Any changes must be made permanent by saving them with UpdateConstants.vi.

4.3 Slave PC

The Slave PCs are built from a group of identical PCs each equipped with

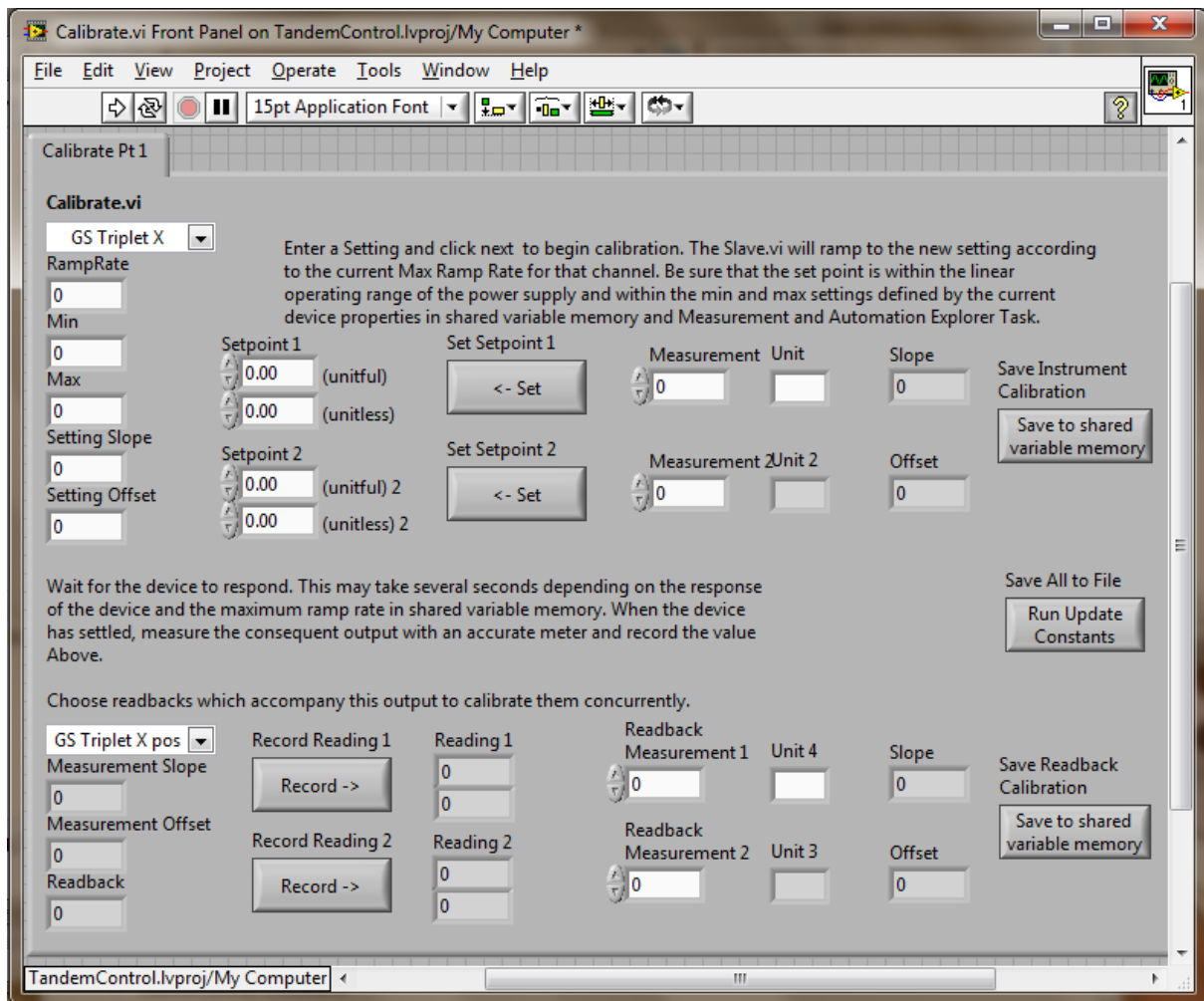


Figure 4.5: Calibrate.vi

- Pentium 4 processor
- 512MB DDR memory
- Intel Pro/100 PCI network adapter
- Onboard Serial, USB
- Optional PCI GPIB Adapter
- NI PCI 6703 Multifunction DAQ
 - 16 channels Analog Out
 - 8 Digital I/O
- NI PCI 6013 Multifunction DAQ
 - 16 channels 16bit Analog In
 - 8 Digital I/O + Freq Out

4.3.1 Local Memory and Network Variable Access

Since it is desired that the Slave PCs operate normally under conditions of network interruption, the use of network variables has been carefully examined to eliminate detrimental effects. The Slave PC must access the Master PC to retrieve calibration information. If the Master PC is out of communication, or its Shared Variables are not properly Deployed or contain Null data, then the Slave PC has a risk of outputting incorrect programming information to its dependent instruments. To avoid this condition, the information is accessed, tested, and then copied to local memory, which is used in all calculations. The result is that under any of the previously mentioned conditions, the local memory buffer simply ceases to be refreshed, and the Slave operates with its last valid set of parameters.

The array of setpoints is handled slightly differently. For these, each Slave PC hosts a network shared variable in its own memory. Since the Shared Variable is hosted in local memory, it shares all of the above mentioned benefits, but it can be updated asynchronously by any VI which performs a network write operation. It was concluded that this method was able to achieve the most responsive operation.

4.3.2 Governor

The Governor is a SubVI which is used to protect the power supplies driven by the Slave PCs by limiting the programming signal they receive. Many of the power supplies used in the lab are considerably old and may lack sophisticated protection circuitry and automatic error recovery. Additionally, many of the optical elements that are driven by these power supplies represent capacitive or inductive loads. Magnetic lenses, for example, are driven by a constant current supply. Due to the large inductance of the lens, a sharp increase in programmed current will cause the power supply to overload, and the power supply will need to be reset by hand to clear the error status.

The Governor simply compares the current value of the programming signal to the target setpoint chosen by the user and limits the rate of change of that signal until the output matches the target value. It also ignores setpoints outside the valid range of the supply, defined by the Min and Max variables.

4.3.3 Channels and Timing

Each Slave receives a 20 element array of setpoints, transmits a 20 element array of measurements, and accessed a 20 element subset of each parameter array defined by Settings.lvlib and Measurements.lvlib. (Sec 4.2.1)

Sixteen of these array elements are used to relay the Analog IO between the NI Multifunction DAQ PCI hardware and the Master VI. These array indexes are reserved in such a way that there is a predetermined correspondence between the array index and the Slave hardware channels. The remaining four can be configured as needed by the Slave PC to interface with less standard devices, which may require communication in the form of a TTL frequency signal, Serial RS-232, GPIB, or USB.

The Slave VI is programmed to execute three parallel loops, each with a different iteration delay. The timing for these loops is non-critical and is derived from the PC system clock.

- Governor and DAC out - 100 iterations per second

This loop reads the array of setpoints from the Network Shared Variable resident in its own memory and processes that information through the Governor SubVI. The resulting array is given to the DAQmx VI that updates the Digital to Analog Converter channels on the NI PCI 6703 Multifunction DAQ hardware. This loop also includes any alternate output protocols which are required to communicate with unique devices.

- ADC in - 20 iterations per second

Reads the ADC channels from the NI PCI 6013 Multifunction DAQ card via the DAQmx VI. This VI returns an array with the voltage of each ADC channel in floating point decimal format with units of Volts. The PCI DAQ card is pre-configured to sample continuously at 10kHz per channel with timing derived from the card's onboard 20MHz oscillator. Between loop iterations, the PCI card automatically samples the voltage and fills its onboard memory buffer with the data. The VI reads a two-dimensional array and averages the samples for each channel, reducing the dimension by one. The timing for this loop is chosen so that this averaging filters out the abundant 60Hz noise present on the measurement, since each iteration includes three 60Hz cycles. After averaging, the measurements are sent back to the Master PC.

- Update Calibration Parameters - One iteration per 10 seconds

The calibration parameters are read from the Network Shared Variables hosted on the Master PC and the proper subset is extracted. The loop checks for clear error status before updating its local memory with the subset.

4.4 Exceptional Cases

4.4.1 Danfysik

The Danfysik magnet power supply is currently the only device on the system which uses serial RS-232 protocol for communication. The Slave VI interacts with this power supply similarly to other devices on the system, simply issuing the desired setpoint via a serial command word instead of an analog voltage. However, the power supply is capable of reporting quite a bit of information about its operation and status. To take advantage of this additional potential, a VI specifically tailored to the Danfysik was written by a summer student, Cornelius Aschermann, which can be used to troubleshoot the power supply, and issue special commands.

4.4.2 Electrometer

The Electrometer (Keithley 487 picoammeter/voltage source) is used to measure the beam current collected by the Faraday cup. It is capable of measuring the current with a selectable range from picoamps to milliamps. The device displays the measurement on a digital display with 3.5 digits of precision, and also provides an analog voltage output of 0-5Volts full-scale, with which is very convenient to interface a Slave ADC channel. The Keithley 487 utilizes a GPIB interface for communication with the Slave PC, which is necessary for range selection.

Since there are several Faraday cups at different positions along the beamline, it was necessary to devise a method of switching which Faraday cup current would be measured by the Electrometer at a time. The solution to this is a circuit designed and implemented by an undergrad research assistant, Will Lunden, which consists of a circuit board with several DPDT reed-relays that select one Faraday cup at a time for measurement while grounding the rest, as well as special modifications of the Slave VI needed to control the relays and GPIB communication.

4.4.3 Tandem Terminal Voltage stabilization - GVM/Beam

The Slave PC referred to as the Tandem PC performs a function that is quite different from the others and extremely important to the operation of the facility. This PC is responsible for regulating the Tandem Terminal Voltage and is the only Slave that completely abandons the model Slave VI, although it still conforms to the standard Slave PC hardware and software architecture.

The Tandem PC runs a specialized VI that replaces both the Generating Voltmeter (GVM) and Beam stabilization methods previously implemented in hardware, resulting in a software selectable choice of regulation method. These two methods are detailed throughly in R. Hellborg - Electrostatic Accelerators(1, pp 153-162)

The simpler and more reliable of these two methods is Beam Stabilization, wherein two conductive plates are inserted on either side of the beam after a 90° magnetic bend. As the beam passes through the Slit formed by these two plates, some of the beam current is collected

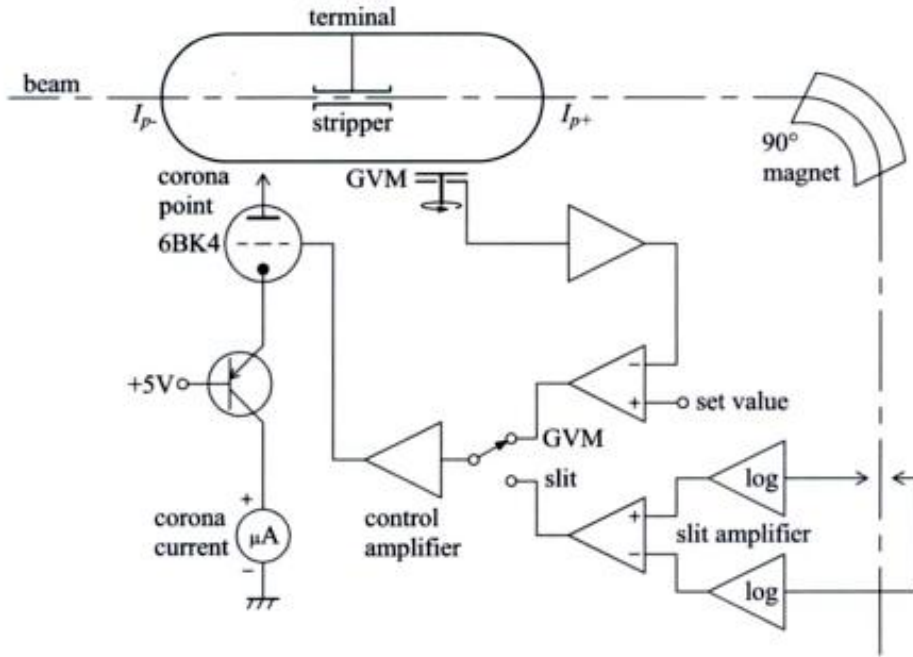


Fig. 9.2. Standard stabilization system of a tandem accelerator

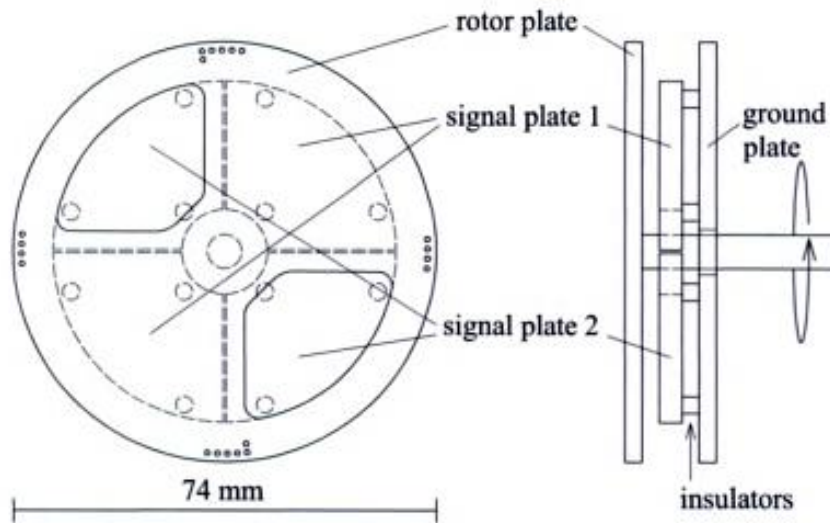


Fig. 9.3. Generating voltmeter (GVM)

Figure 4.6: Excerpts from (1, Electrostatic Accelerators)

by either plate. A simple logarithmic difference amplifier provides negative feedback to the control amplifier. The result is that the Terminal Voltage is regulated to maintain the beam in the center of the two plates. The Tandem VI emulates this action by measuring the output of the logarithmic amplifiers with a differential ADC and calculating an error signal digitally.

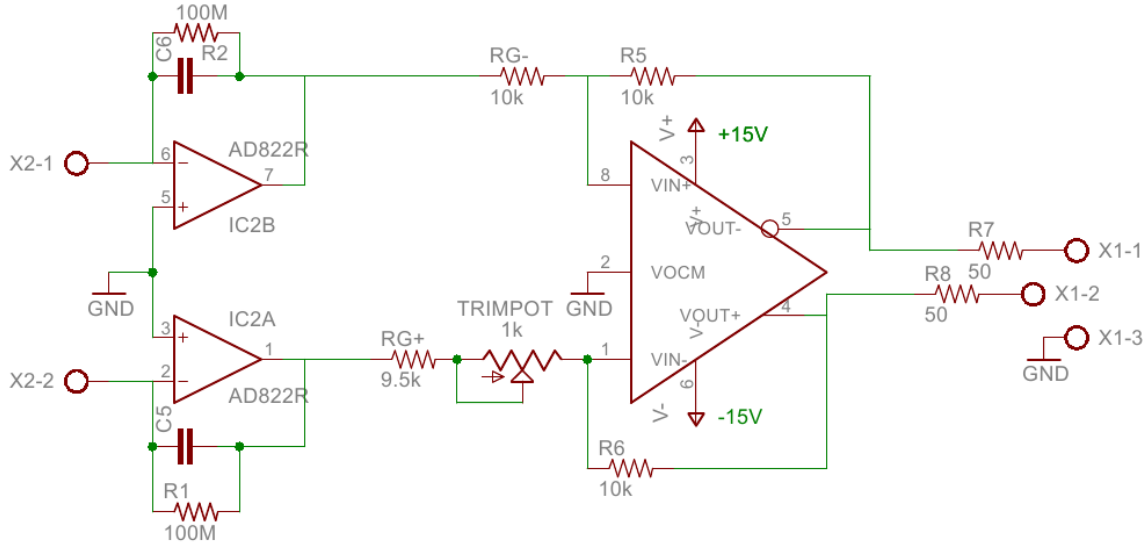


Figure 4.7: GVM Charge to Voltage Amplifier and Line Driver

However, as stated in Electrostatic Accelerators,

“For some experiments, for example in accelerator mass spectroscopy, the terminal voltage must be stabilized even in the absence of a measurable beam. In this case a generating voltmeter (GVM) is the most accurate tool for voltage measurement and stabilization.”

Since AMS is exactly what is intended, the Tandem PC has been equipped with a new approach to stabilize the Terminal Voltage utilizing the GVM.

The GVM consists of a number of signal plates, known as stator segments (see Fig. 4.6), which are placed on the wall of the Tandem VdG tank and have some finite capacitance with respect to the Terminal. Instead of the capacitance remaining constant, it is varied by the rotation of a grounded Rotor Plate. When a segment is uncovered, a charge proportional to the terminal voltage is induced, and as the rotor turns, a current flows between alternate sets of segments. The amplifier shown in Fig. 4.7 was designed to measure the charge induced on the Stator Segments due to the terminal voltage. This circuit contains two op-amps in a configuration known as an Op-amp Integrator, the output of which is the integral of the input current, I_{Int} , in Volts (Eq. 4.2). Following the two Integrators is a Difference Amplifier, which subtracts the two outputs and prepares the signal to be transmitted through a 100 Ω shielded twisted pair to the differential ADC of the Slave PC. The resultant waveform looks like a triangle wave.

$$I_{GVM} = V_T \frac{dC_{GVM}}{dt} \quad \text{Current between GVM Segments(1)} \quad (4.1)$$

$$I_{Int} = C_{Int} \frac{dV_{out}}{dt} \quad \text{Current through Integrator Cap} \quad (4.2)$$

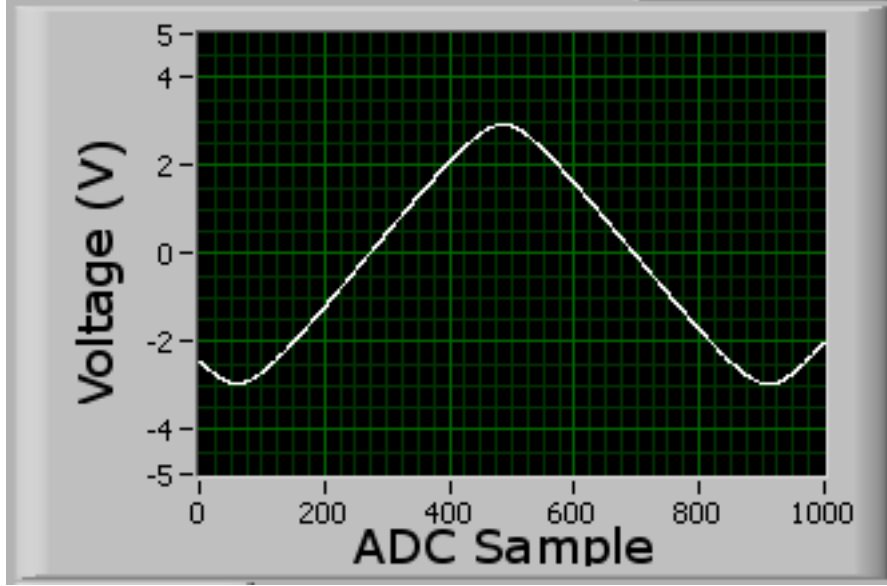


Figure 4.8: Triangular GVM Waveform

The amplifier is inserted in series between adjacent Segments, making $I_{Int} = I_{GVM}$

$$\begin{aligned}
 C_{Int} \int dV_{out} &= V_T \int dC_{GVM} \\
 \therefore V_{out} &= V_T \frac{C_{GVM}}{C_{Int}} & C_{GVM} &= C_0 \text{Triangle}(t)
 \end{aligned} \tag{4.3}$$

C_{Int} was chosen to be on the order of $10^{-6}C_0$, 1 nanoFarad, making the output waveform amplitude about 1V per 1MV of Terminal Voltage.

GVM regulation relies on an accurate measurement of the amplitude of this triangular signal. For AMS purposes, accuracy of about one part in a thousand, or 0.1%, is desired. The GVM amplifier must therefore be sensitive to about one pico-Coulomb of charge on the GVM stator segments, while rejecting undesired interference. Unfortunately, magnetic coupling between the GVM motor itself and the stators introduces a noise signal greater than ten times this level. To remove this noise, a method similar to that of a Lock-In Amplifier was programmed into the Tandem VI.

The Lock-In method takes advantage of the fact that the time average of two multiplied sinusoids equals zero when averaged over an interval much longer than the period of the multiplied signals, unless they have an identical frequency. By multiplying a noisy signal by a sin wave at a particular frequency and then filtering out all but the DC component, the Lock-In Amplifier behaves like a bandpass filter with an extremely small bandwidth.

The Lock-In method filters out all component frequencies other than the fundamental harmonic, which is about 235Hz. This is valid because the amplitude of the Triangle wave is proportional to the amplitude of that component.

$$\begin{aligned} Triangle(t) &= \frac{8}{\pi^2} \sum_{k=0}^{\infty} (-1)^k \frac{\sin((2k+1)\omega t)}{(2k+1)^2} \\ &= \frac{8}{\pi^2} \left(\sin(\omega t) - \frac{1}{9} \sin(3\omega t) + \frac{1}{25} \sin(5\omega t) - \dots \right) \end{aligned} \quad (4.4)$$

The Lock-In method takes advantage of the property of orthogonality of sinusoids

$$\int \sin(n\omega t) \sin(m\omega t) dt = \frac{1}{2} \delta_{nm} \quad (4.5)$$

To mimic the Lock-In behavior, a reference signal must be available with the exact frequency of the GVM signal. The reference signal is derived from the GVM signal itself, using a Zero-Crossing Detector, which outputs a digital logic signal that changes value depending on the sign of the bipolar GVM waveform. The resulting signal is TTL compatible with a 50% duty cycle, at the fundamental frequency of the GVM triangle wave. It is input into a Phase Locked Loop(PLL) that multiplies the frequency by 256, yielding 60.1kHz, using the rising edge to trigger each ADC sample of the GVM waveform, allowing the Tandem VI to read exactly 256 samples per period, and maintain a constant phase relationship of each sample to the GVM waveform.

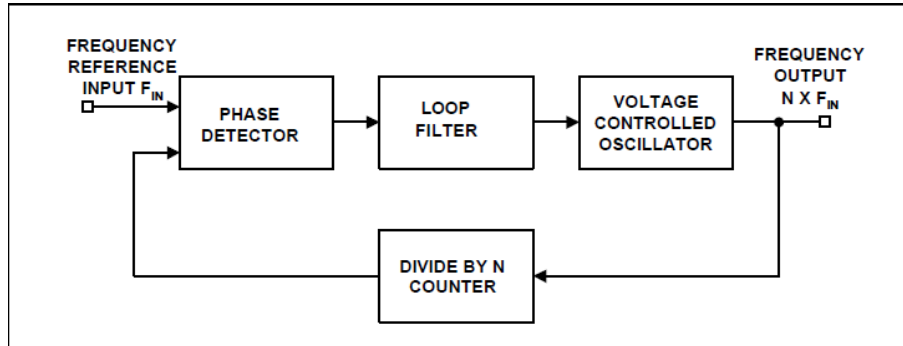


Figure 4.9: PLL simplified block diagram(4). In this application, F_{In} is obtained from the Zero Crossing Detector, and the output, $256 \times F_{In}$, is the ADC Conversion trigger.

Since the synchronization is done via the external circuitry, the Tandem VI is left with the task of multiplying the ADC samples point by point with a reference sinusoid created from the sample number. Finally, the result is entered into a running average of configurable length. To remove any error due to phase offset between the reference and GVM signal, the VI generates both sine and cosine waves and combines them in square after averaging.

The interval of the running average introduces a delay in the measurement, thus there is a trade off between accuracy and delay. The longer the averaging interval the more unwanted signals are removed, but the desired signal is also averaged and therefore lags behind the true value. It is well known that any delay introduced in a closed loop control system can cause

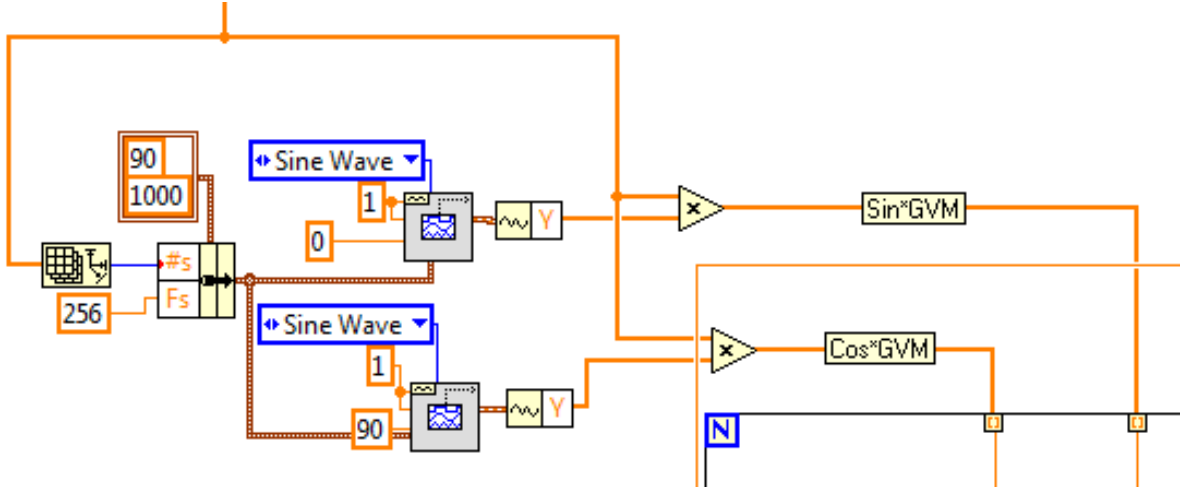


Figure 4.10: The reference Sine and Cosine are produced in software from the number of samples collected by the ADC. After multiplication with the GVM signal, they are averaged over a period of 100 GVM cycles, 0.42 seconds.

instability. Considering this, the interval was adjusted to about 0.4 seconds to achieve a balance that gives the best accuracy and stability of the control system. The result of this averaging is then passed into a Proportional Integral Derivative (PID) VI that calculates a control signal with many configurable parameters.

The equation to calculate the PID control signal is as follows:

$$e = \text{SetPoint} - \text{ProcessVariable} \quad \text{Error}$$

$$u(t) = K_c \left(e + \frac{1}{T_i} \int_0^t edt + T_d \frac{de}{dt} \right) \quad \text{Controller Action}$$

The gain constants, K_p , T_i , and T_d , were found using the Ziegler-Nichols method of PID parameter tuning(5), setting T_i and T_d to zero, and increasing K_p until the control system begins to oscillate and noting the gain, K_c and period of oscillation, P_c . The PID parameters are then set to

$$K_p = 0.45K_c \quad T_i = 0.6P_c$$

Making this a PI type controller.

4.4.4 Beam Profile Monitor

The Beam Profile Monitor(BPM) is used to view the profile of the beam spot in the horizontal and vertical axis. It consists of a helical wire spinning along its axis, sweeping through the beam alternatively horizontally and vertically. The current collected during this sweep is plotted, giving a X and Y profile over a period of time. The phase of the helix's rotation is locked to a fiducial signal which is derived from a magnetic sensor. A custom timer is used to synchronize the sampling of the BPM with the fiducial signal.

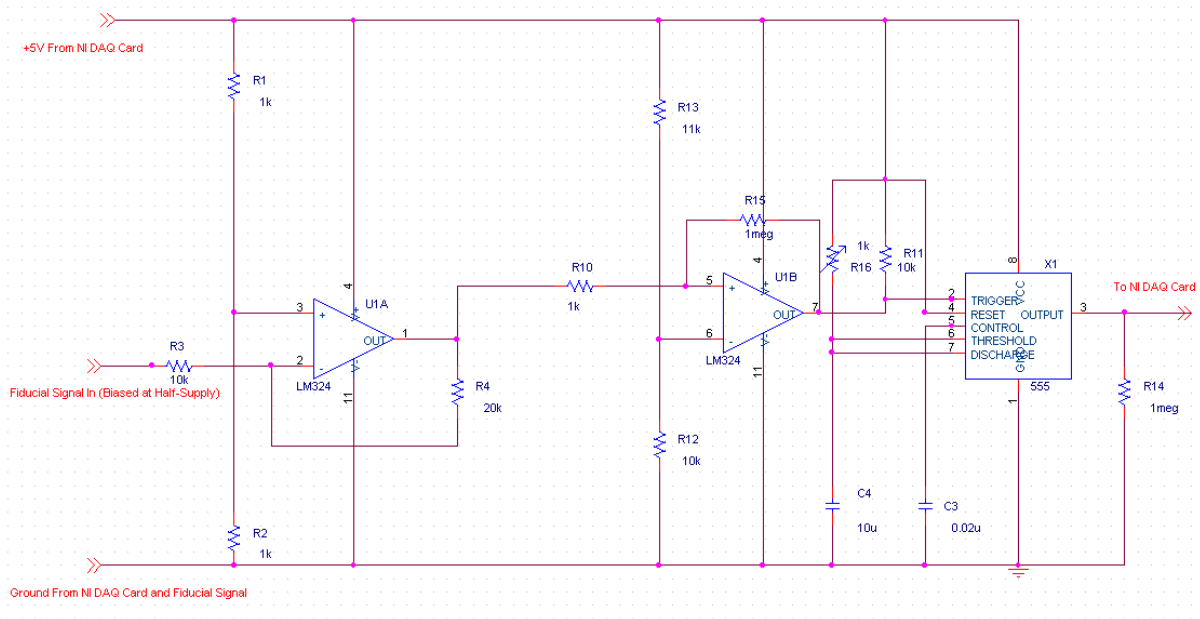


Figure 4.11: Fiducial timing circuit. A 555 timer is configured as a Monostable Re-triggerable Multivibrator, triggered by a level sensor.

The timer detects a gap in the pulse train from the fiducial sensor which signifies the completion of one rotation. Upon resumption of the pulse train a rising edge is transmitted to the National Instruments PCI DAQ card, which is configured to begin sampling the BPM signal by an altered version of the Slave VI running on the Analyzer PC.

In order to service multiple BPM devices throughout the facility, an additional relay board was constructed to switch one BPM signal at a time into the fiducial timer and ADC. The relays are driven directly by the digital output channels available on the National Instruments DAQ card.

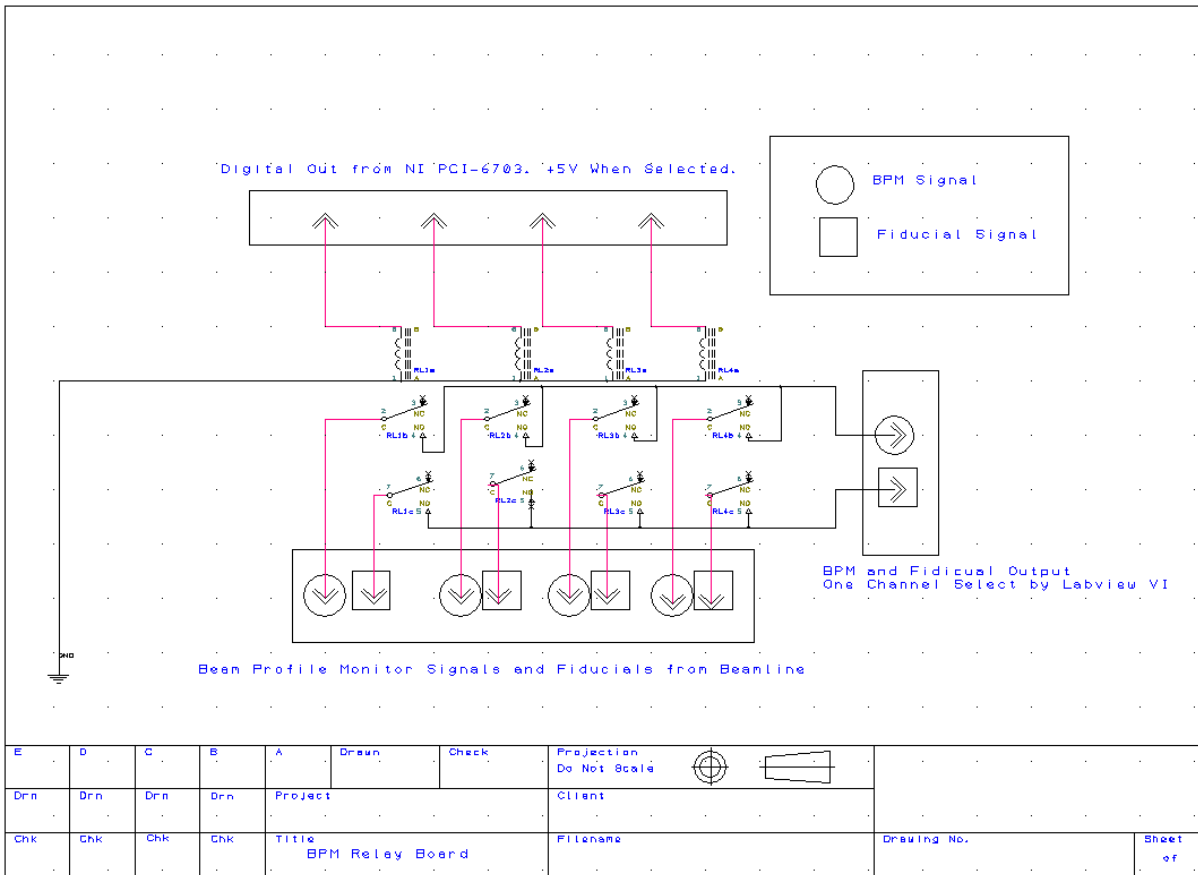


Figure 4.12: DPDT reed relays select one BPM signal and its fiducial signal to be transmitted to the fiducial timer and ADC.

5

Results

5.1 Response Rate

The Master VI is programmed to update the set points immediately upon user interaction, while each Slave PC updates its output channels every 10 milliseconds, and transmits the measurements of its input channels every 50 milliseconds. TCP/IP communication over the gigabit internal LAN adds an estimated 10-100 milliseconds each way, so in worst case scenario the user may experience about 0.25 seconds of lag introduced by the control system alone between making an adjustment and observing a response from the device. This estimate is conservative and a more typical delay of less than 100 milliseconds is more likely, which is hardly noticeable by users. This small delay is outweighed by the time saved by the point and click interface and the availability of all devices from one location.

The response rate of the optical elements in the beamline, however, is much longer. Some magnetic components such as the Analyzer Magnet may take 30 seconds to settle to their ultimate value. This settling time is the constraint that sets the response rate of the system upon loading a previously saved set of tuning parameters. It is expected that the time to automatically switch between two saved tunes for different isotope beams should take about one minute including several in-range status and interlock checks to be on the safe side.

5.2 GVM Response

The GVM analysis routine is able to achieve a measurement with better than one part in a thousand precision. When used as the regulation parameter it is able to meet the stability requirements for Accelerator Mass spectroscopy.

The GVM measurement exhibits a slow drift which causes the beam to veer off target on a time scale of about 90 minutes. It is believed that the source of this is thermal gain and offset drift due to components in the prototype GVM amplifier. Careful selection of components for a final version of the amplifier may potentially improve this result. Alternatively, a correction routine may be implemented to correct the drift by switching to beam stabilization periodically and noting the Terminal Voltage as measured by the GVM.

Figure 5.1:

Chart of the Terminal Voltage based on the measured GVM waveform over a period of two seconds. This was recorded while the Terminal Voltage was regulated by the "Beam" stabilization method at about 2.8 Megavolts. Notice the thickness of the line, about 100Volts or 0.003% of total.

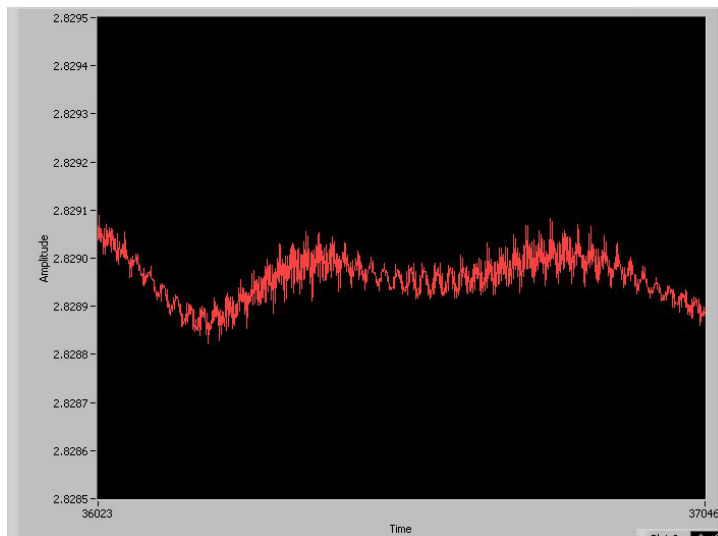
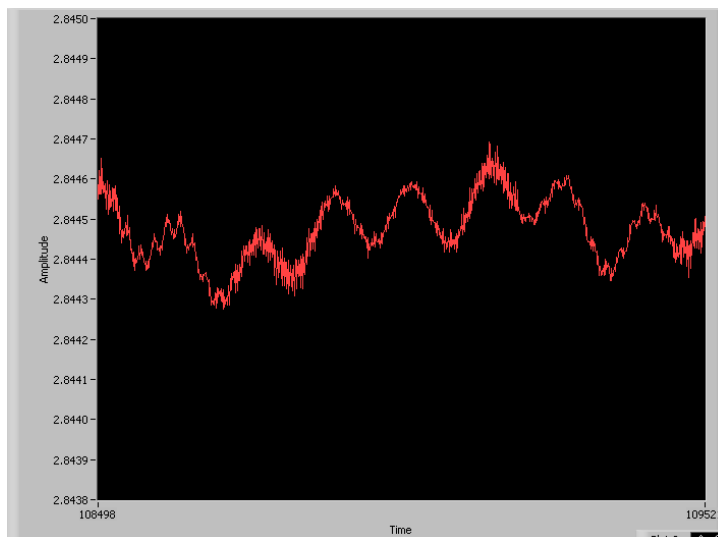


Figure 5.2:

Chart of the Terminal Voltage during "Beam" stabilization with the gain increased to produce oscillation to show that variations in the Terminal Voltage of less than 100Volts are clearly visible.



5.3 Expandibility

5.3.1 Automation

The facility will be upgrading to a sample changing ion source which will require a servo motor controller. A new VI is planned to cycle isotopes and control beamline components in order to collect and log measurements of each batch of samples. The VI will be designed to step through a number of beam tunes, making measurements, logging results on the internet. It is important to confirm the reading of each important instrument is within a tolerable range before moving from one phase of the measurement to the next, accounting for the settling time of magnets, faraday cup status, vacuum tolerances if necessary, or any other concern.

5.3.2 Additional Slaves

Additional Slave PCs may become necessary in the future, so the control system has been designed so that they may be added as easily as possible. The new PC must conform to the

standards of the existing Slave PCs. Each slave PC requires several elements in the LabVIEW Project.

- Shared Variable array of [20] floating point numeric elements located in Measurements.lvlib
- Shared Variable cluster of error elements located in Status.lvlib
- Shared Variable array of [20] floating point numeric elements located in a new library hosted on the additional Slave PC
- Shared Variable array of [16] boolean elements located in a new library hosted on the additional Slave PC
- Copy of the model Slave VI edited to select the correct subset of calibration constants

The existing Master VI must be updated to reflect additional devices by creating additional indicators and event handlers, and the SendSetpoint SubVI must be updated with the newly added Shared Variables hosted on the additional Slave.

Finally, valid entries must be appended to the Shared Variable Arrays in Measurements.lvlib and Settings.lvlib responsible for Min, Max, Ramp Rate, Slope, Offset, etc. in update constants.vi

6

Conclusion

6.1 Complete manual control of beamline

The primary goal of this project was to create a control system that would enable students to directly interact with every element of the beamline from Ion Source to Target. The new control system allows users with no experience to perform nuclear physics experiments from one location. This resource bridges many different areas of physics and levels of understanding. It became an optional experiment in the Senior and Graduate Laboratory course (PHY445/515) in Fall 2010.

In addition to the Instructional Lab, it has been used for multiple educational programs directed toward different audiences. By July 2011, it has been used by about 30 Women In Science and Engineering (WISE) university freshman, 14 PHY515/445 Students, 20 highschool teachers, and 10 highschool students, and it continues to provide opportunities for summer REU student projects as additional improvements are underway.

6.2 Planned additions

The secondary goal of the project was to make additions required for Accelerator Mass Spectroscopy possible. The system is currently able to switch between previously defined beam tunes at the click of a button, adjusting all of the necessary beamline elements required to select a particular isotope. The model Slave PC will be fully compatible with the Sample Changing Ion Source that will allow quick selection of source material. The new Ion Source is currently under testing.

Within the framework of the control system architecture it will be possible to introduce an additional VI capable of automatically isotope switching and sample cycling without the necessity of altering any other system component.

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