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A Use of Theory of Constraints Thinking Processes for Improvements in the Merged Beams Experiment at Oak Ridge National Laboratory.

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A Use of Theory of Constraints Thinking Processes for Improvements in the Merged Beams Experiment at Oak Ridge National Laboratory

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by

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ABSTRACT

A Use of Theory of Constraints Thinking Processes for Improvements in the Merged Beams Experiment at Oak Ridge National Laboratory

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Thinking exercises used in the Theory of Constraints (TOC) were used to find and remove constraints at the Merged Beams Experiment at Oak Ridge National Laboratory. The goal of this project was to significantly reduce the amount of time used to take a certain type of measurement during an experimental cycle. After the TOC exercises were used, a basic plan for change was discovered. Preliminary data were taken to establish a baseline of performance from which changes were made. Post-Modification was analyzed showing the project was a success.

The overlying reasoning for this exercise was to prove successfully that continuous improvement techniques used in the manufacturing industry can also be successful in a research environment. After overcoming the differences in the goals between each environment, it can be concluded that this reasoning is justified.

DEDICATION

To my family: Jessica, Eli, and Dad. Thank you for being supportive and loving.

"Finally, brothers, whatever is true, whatever is noble, whatever is right, whatever is pure, whatever is lovely, whatever is admirable—if anything is excellent or praiseworthy—think about such things."

- St. Paul. Philippians 4:8

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CHAPTER 1

INTRODUCTION

Continuous Process Improvement (CPI) is a term used on an everyday basis in public industry. Industries that specialize in manufacturing or service are normally involved in some sort of manufacturing technology that involves CPI. However, it is not a term that is widely used in science programs such as the Merged Beams Experiment at Oak Ridge National Laboratory. In this particular project, improvement of the Merged Beams Experiment is considered. Continuous improvement methods used in the Theory of Constraints (TOC) is used to identify "bottlenecks" in the merged beams experimental process. These methods should help those involved find ways to alleviate these bottlenecks.

What defines a bottleneck? "A bottleneck is any resource whose capacity is equal to or less than the demand placed on it (Goldratt & Cox, 1984)." To the point in the Merged Beams Experiment a bottleneck is a resource that restricts the flow of good data for the experimenter. The TOC methods that should alleviate these bottlenecks are three thinking exercises that help organizations define bottlenecks (constraints) and alleviate them. These three thinking exercises are the Current Reality Tree, Evaporating Cloud, and Future Reality Tree.

In this thesis through these continuous improvement methods the goal of the experiment is presented. From these techniques solutions are identified and applied to mitigate bottlenecks to move the experiment closer to the goal.

CHAPTER 2

BACKGROUND INFORMATION

Merged Beams Experiment

In the merged beams experiment at Oak Ridge National Laboratories, the objective is to measure low energy charge transfer cross sections at low collision energies. In the Merged Beams Experiment this cross sectional measurement is performed as a function of the collision energy. The collision energy is measured at the center of mass frame. The neutral beam and the molecular beam collide at the collision energy. Equation 1 expresses this energy in mathematical form (Havener, 1997). This is an expression of the relative energy of the collision of two ion beams. Erel is the relative energy in the center of mass frame that is one half of the square of the relative velocity of the two merged beams. E1 and E2 is the energy of beam 1 and beam 2. The atomic mass of each beam is expressed as m1 and m2. The energy of the beam is expressed as electron volts (eV). Cosine (θ) is the angle of intersection for the two beams (Havener)

$$Erel\left(\frac{eV}{amu}\right) = \frac{E1}{m1} + \frac{E2}{m2} - 2\sqrt{\frac{E1E2}{m1m2}}\cos(\theta) \qquad (1)$$

Collision energy for Ion Beam Overlaps (adapted from Havener, 1997)

The center of mass frame measurement is accomplished by merging two relatively fast ion beams. An ion source produces a negative hydrogen ion beam. To be effective, the ion beam needs to be operated from 6 to 9 ke'V. An analyzing magnet and electrostatic elements focus the beam for intensity and steer the beam into the path of a high intensity laser. The light from the laser excites the valence shell of the ion detaching an electron. This creates a neutral (H_0) beam. Simultaneously, an Electron Cyclotron Resonance (ECR) ion source creates a beam at energy E_2 ranging between 20 and 60 ke'V of atomic or molecular ions. The beams are then merged in a circular chamber with two opposing spherical deflectors (left of center in Figure 1). Here the molecular beam is characterized and tuned to match the horizontal and vertical profiles of the neutral hydrogen beam. After this tuning process, the beams are demerged using a magnet that deflects ions with different charge states into various data collection devices. The H+ ions formed from charge exchange in the circular chamber are detected using a Channeltron electron multiplier. The atomic or molecular ion beam is detected with a Faraday cup. The remaining neutral hydrogen beam is measured using secondary electron emission detection.

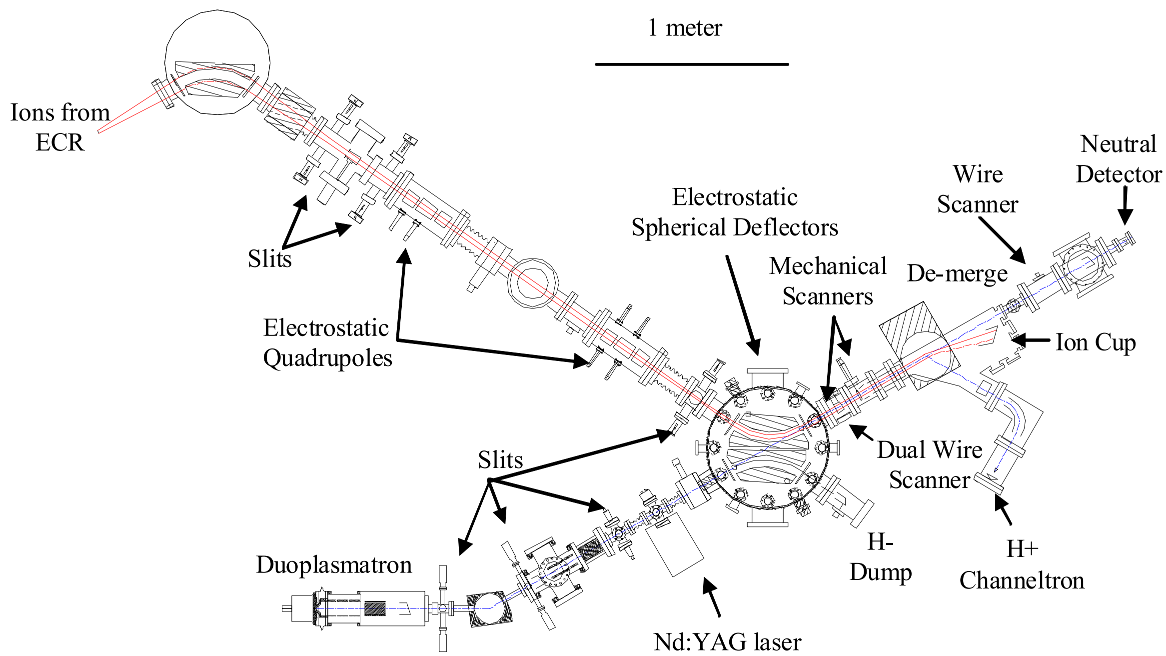

Figure 1. A Diagram of the Merged Beams Experiment Beam Line at ORNL. *From* "Isotope effects in low energy ion-atom collisions*" by* Havener, C.C., Seely, J.D., 2009, In *CP1099 Application of Accelerators in Research and Industry: 20th International Conference, ed F. D. McDaniel and B. L. Doyle, 2009 AIP*, pp 150-153. Used With Permission of the Author

To monitor and record certain beam characteristics two types of beam profile monitors (BPM) are used: two rotating wire scanners and two slit scanners. Kmax software controls a CAMAC Sparrow control module that controls a motor for each slit scanner. The motor pushes the slits into the path of the beam. Data from the slit controller are transmitted to a data acquisition system. When scanning, these slit scanners interrupt the beam and are used intermittently to make measurements.

The wire scanners are used to monitor intensity, horizontal, and vertical aspects of the beam at different positions of the beam line. Monitoring the horizontal and vertical profiles from a wire scanner upstream and downstream is a good indicator of the need for optical corrections. These measurements can be made with conducting wire beam profile monitors. Unlike Slit scanners, this method does not interrupt to the beam and is the preferred method of beam characterization (Seely, 2008).

Havener, a physicist and principle scientist involved in the merged beams experiment, helped design and patent the modification to the single wire scanner. The modification included the addition of a second conducting wire to a rotating helical beam scanner. Through permissions granted by Havener and ORNL a prototype dual-wire scanner was fabricated by National Electrostatics Corporation (NEC). Presently, the BPM 280 dual wire Beam Profile Monitor from NEC has been successful in characterizing the merged beam and has mitigated tuning problems associated with single wire scanners. The use of the BPM 280 increased accuracy of measurements by providing two independent x and y profiles. It is this BPM that is used for characterizing beam overlap measurements before taking final overlap data. Figure 2 shows a dual wire BPM setup at two different viewpoints. The wires pass through the beam line and detect certain characteristics.

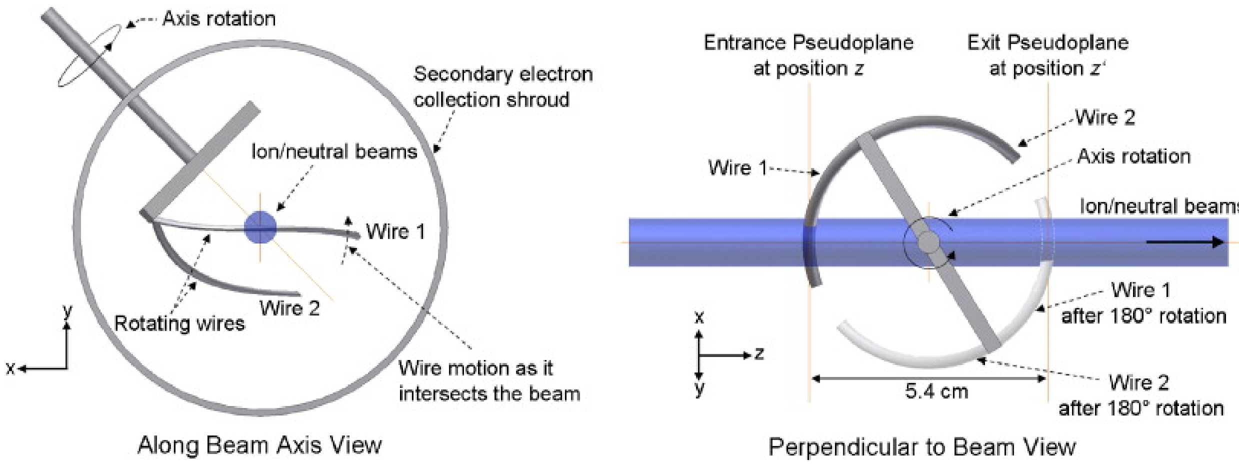

Figure 2. A Cross Sectional View and a Perpendicular View of a Dual Wire Scanner in Reference to the Beam Line. From "Rotating dual wire beam profile monitor optimized for use in merged-beams experiments," by Seely, D.B., Bruhns, D.W., Savin, T.J. Kvale, E., Galutschek, H., Aliabadi, Havener C.C. 2008, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 585, 1-2, 69-75. Used with permission of the author.

Data Analysis

BPM data are used to determine the cross section measurement as a function of (center of mass frame) collision energy. To obtain this information one must calculate the overlap of the beams at each collision energy. "Cross sections are determined by measuring the signal produced by the beam-beam interaction over the merged length L (Havener, 1997). The mathematical model for calculating the cross section in merged beams is as follows:

$$\sigma = \frac{R}{\varepsilon}\frac{\gamma q e^2}{I1I2}\frac{v1v2}{vr}\frac{1}{L\Omega} \qquad (2)$$

Cross section Measurement Expression (adapted from Havener, 1997)

In this equation R, I1, and I2 correspond to the H+ signal count rate, effective current produced by neutral particles, and heavy ion beam current, respectively. The expression R/ε is representative of the true signal rate. ε is the efficiency of the Channel Electron Multiplier (CEM) and the electronics which detect H+ at velocity $v1$. $\gamma/I1$ is an expression of the true neutral current. γ is the measured effective secondary-electron emission coefficient for the neutral-particle detector. The section of the equation involving the product of q and e are related to charge where q is the charge of the ion, and e is the electronic charge. vr is the relative velocity of the two beams. Ω represents the overlap integral along the merge path L (Havener, 1997). Ω can be expressed by the following:

$$\Omega_{(z)} = \frac{\int I_1(y)I_2(y)dy \int I_1(x)I_2(x)dx}{\int I_1(y)dy \int I_1(x)dx \int I_2(y)dy \int I_2(x)dx} \quad (3)$$

An Expression of Ω in Reference to Beam Overlaps at a Particular Beam Position, z. (adapted from Havener, 1997)

In the previous equation, z is the direction of propagation for the beam and xy represents a plane of perpendicularity of the beam (Havener, 1997). I_n represents the given beam current. This equation is a two-dimensional area measurement of the beam overlap. This measurement is taken at different points along the beam line and used as an approximation of a 3-dimensional overlap measurement. Expressed simply, Ω is representative of the measurement of the overlapped beams where they merge (Seely, 2008). The overlaps are measured by the rotating wire beam profile monitors mentioned earlier. Figure 3 expresses the final data in graphical form.

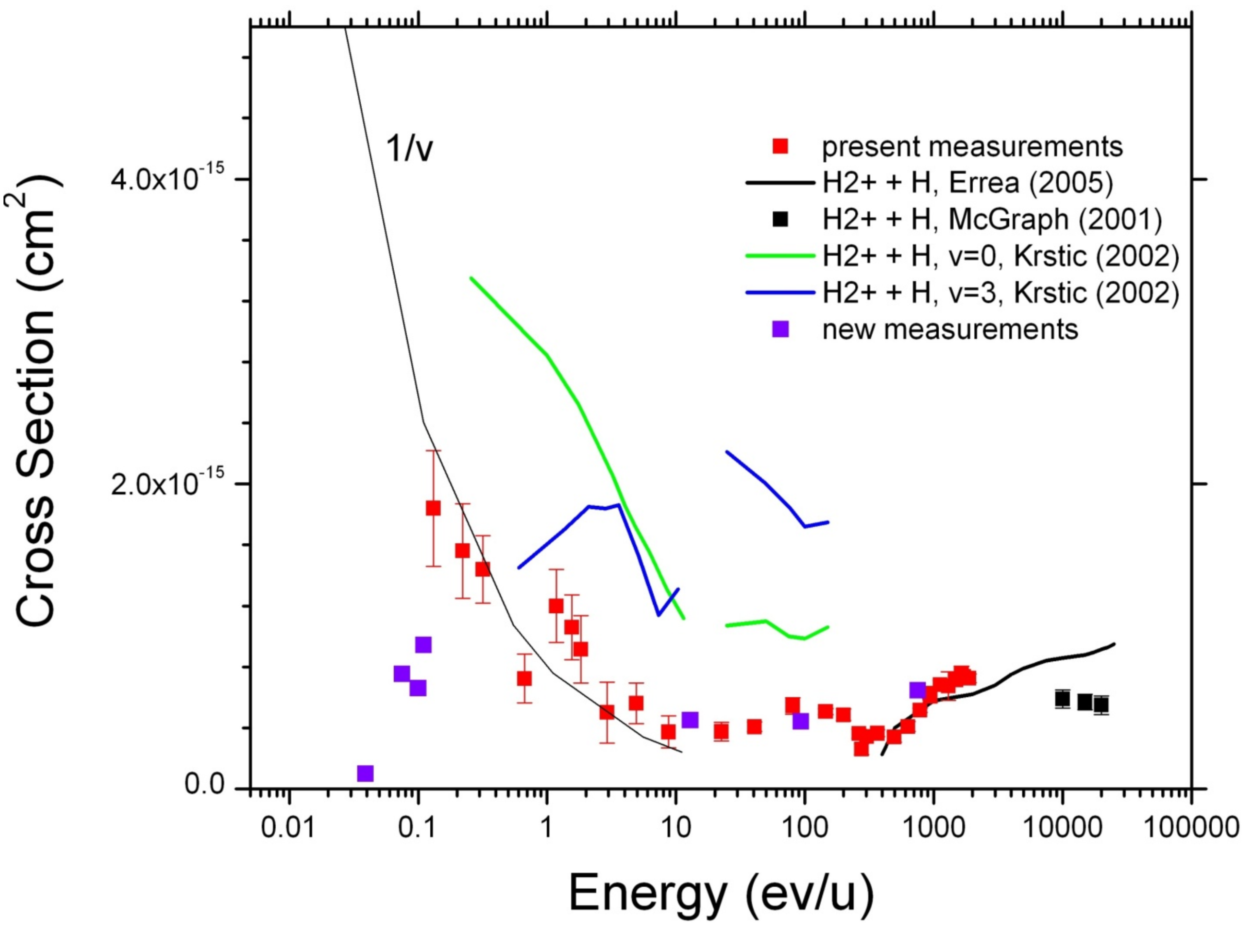

Figure 3. Merged Beam Cross Section as a Function of Collision Energy. From "Investigation of charge transfer in low energy D2+ + H collisions using merged beams," by Andrianarijaona, V. M., Rada, R. Rejoub, J. J., &. Havener, C. C. 2009, *ICPEAC 2009 proceedings, Kalamzoo, MI.* Used with permission of the author.

The aim of the Merged Beams Experiment is to investigate charge exchange mechanisms at very low relative energies. Their future goals include the attachment of an x-ray detector to the target area to provide the ability to study low energy x-ray emissions. For example, when charge exchange occurs in the solar wind, the highly charged ion that bonds with an electron emits an x-ray as the excitation phase relaxes. Studying these charge exchanges in the Merged Beams Experiment will help researchers understand which x-rays come from solar wind and which do not. Charge exchange also occurs in fusion plasma. At 80 million degrees Celsius, highly charged ions are produced. Charge exchanges here take place with neutrals near the plasma edge or are contained in diagnostic neutral beams.

Theory of Constraints

Description

Stated in the Theory of Constraints (TOC), there are three measurable aspects in any production system (Goldratt & Cox, 1984).

1. Throughput: The rate at which the system generates money through sales
2. Inventory: All the money the system has invested in purchasing things that it intends to sell
3. Operational Expense: All of the money the system spends in order to turn inventory into throughput (Goldratt & Cox, 1984)

TOC also states that there is a constraint or multiple constraints in every system and that constraint limits the amount of throughput in the system. The throughput is limited by the amount of inventory behind the constraint (Elssamadisy & Mufarrige, 2007). Relieving the constraint reduces inventory and increases throughput therefore lowering operational expense (Goldratt & Cox, 1984).

Figure 4 shows an illustration of a process. Note the bottom of the figure is labeled capacity. The first process is capable of producing 20 parts in a given period of time. The second process however is only capable of turning out 16 parts in a given time. Thus, inventory is going to back up behind the second worker. The third process can only turn out 10 parts piling more inventories behind it. Meanwhile there are few parts at the end of the line waiting to be shipped. This is a good example of a bottleneck. Inventories are backed up and throughput is low. The inability to sell the end product makes operational expense high.

Capacity: 20 WIP: 0	Capacity: 16 WIP: 4	Capacity: 10 WIP: 6	Capacity: 14 WIP: 0	Capacity: 18 WIP: 0	Low: Should outweigh cost of inventory and operational expense

Figure 4. Example of a Constraint

The same principles of TOC that apply to manufacturing systems can also apply to scientific research support. At the Merged Beams Experiment at Oak Ridge National Laboratory, the definitions in described earlier can be tweaked and re-applied to their system. In Goldratt's book "The goal" he states "the goal in a manufacturing system is to make money (Goldratt & Cox, 1984). While manufacturing systems use metrics for achieving the goal such as return on investment, net profit, and cash flow, the same metrics cannot be applied in this research experiment. Nor can the same definition fit for the goal of the Merged Beams Experiment. Instead the goal in this thesis is described as maximum production of good data from the experiment.   One of the time consuming aspects of taking data is the measurement of beam overlaps. According to Havener, the number of overlap measurements in one 8-hour period is a minimum of 16 or one every 30 minutes. In order to make overlap measurements more efficient, constraints must be mitigated.

Measurement efficiency is the key driver for redefining one of the three definitions shown above. Throughput is redefined as the following: The rate at which the system generates usable data through beam operation. Increasing the rate at which this usable data can be generated is now considered the main driver or "goal". This goal enables the use of thinking exercises used in TOC with the purpose of improving the efficiency of the Merged Beams apparatus.

Major Constraints Identified

Identifying the constraints at the apparatus is seemingly simple; determine the section that has the most inventory behind it. The capacity of any manufacturing process is limited by its capacity-constraining resource. Time lost at the constraint is lost forever (Goldratt & Cox, 1984). In this case the time to take beam overlap data was found to be the largest problem with the easiest fix.

CHAPTER 3

PROBLEM STATEMENT

In order to increase output efficiency of reliable data, especially for visiting scientists and students, the principle author of this thesis and the research staff involved in the Merged Beams Experiment at Oak Ridge National Laboratories has identified “bottlenecks” in their production cycle. The intention of this thesis experiment is to mitigate time constraints involved in the operation of the Merged Beams Experiment. Beam time is expensive. Running the experiment takes a lot of resources. Mitigation of time wasting is a key factor to experiment efficiency. One major time constraint is using the beam line end station to take beam profiles during data acquisition.

As observed, the end station of this Merged Beams experiment is a compilation of dated and new technologies. These technologies such as NIM, CAMAC, and various computer languages are necessary to run the research experiment. Although the reliability of these technologies is reasonably stable, the range of operability of them was complicated. Some aspects of taking beam profiles involve manual operation of a system while others are remotely controlled. The systems that are manually operated require the operator to move from the end station control area. Time away from the control area may lead to problems. If the beam profile measurement process is interrupted (for various reasons), the operator would be unaware of its status while away. This means the operator will have to take time to investigate a fault in the system that could have otherwise been easily fixed. One example of a fault is a faraday cup that is in (blocking the beam) when it is assumed to be out. Reasoning for this fault is the lack of much needed status indicators. Several systems have similar indicator problems. If there is no indication of a fault, troubleshooting time increases. Another factor that increases experiment run time is rebooting old computer systems. A computer system failure such as this involves a substantial amount of time.

There is an apparent need for updating and integrating systems necessary to running an experiment. This action item is the largest constraint on the efficiency of machine use. This constraint, when alleviated, will allow users to have more time to concentrate on the more important aspects of their experiments.

CHAPTER 4

SOLUTION

Through the use of some Theory of Constraints thinking exercises, a major constraint of the Merged Beams experiment is identified and actions taken for improvement in the process. Measurements were taken before and after TOC exercises were implemented in order to take the difference into consideration.

Theory of Constraints Techniques

In the project represented by this thesis, the primary thinking processes used are driven by five primary questions. These questions are based on achieving focused improvement (Goldratt, 1990).

1. What to change?
2. What to change to?
3. How to cause the change?
4. Why change?
5. How to maintain the process of ongoing improvement (POOGI)?

Some of the thinking processes driven by these five questions were used in the Merged Beams Experiment: the Current Reality Tree (CRT), Evaporating Cloud (EC), and the Future Reality Tree (FRT) were applied to help solve the problem once the major constraint was identified. Theory of Constraints thinking tools are used to identify problems and open pathways to solving them (Patrick, 2009).

Current Reality Tree

The Current Reality Tree is a simple tool that shows if-and-then statements to help an organization realize its present state (Patrick, 2009). Instead of providing the information in text form it is shown in graphical form. This format is easier for the reader to identify the cause and effect relationships and follow the logic. For the MBE, the group on this improvement project needed a tool for understanding and agreeing on the problems in the system. Figure 5 shows the current reality tree for the Merged Beams Apparatus.

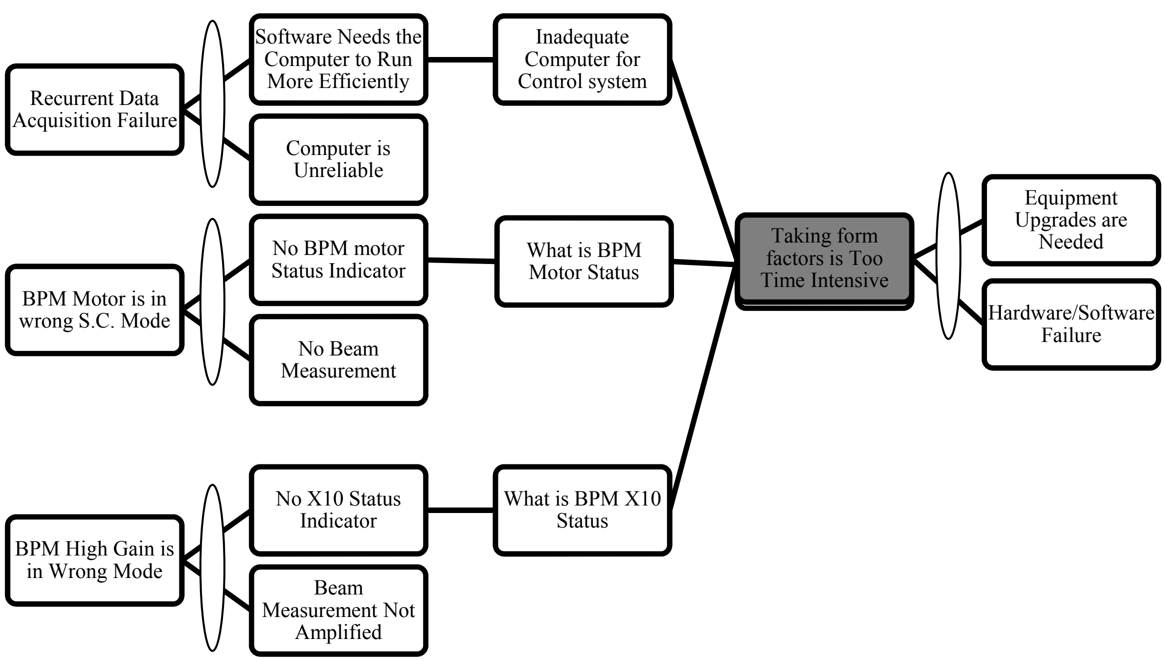

Figure 5. Current Reality Tree for Merged Beams Apparatus

The CRT above depicts cause and effect reasoning where the elliptical shapes represent "and". One block with multiple branches shows the if-then logic. One example shows the logic that concludes that taking overlap data is too time intensive. This conclusion comes from the following statement: If there is a hardware or software failure and equipment upgrades are needed, taking overlap data is too time intensive.

The tree expands on this central statement to state the underlying causes. One major constraint is identified in this logic. The time consumed in taking form factor measurements is the constraint keeping researchers from taking more data points. Because taking data is the most important task in the process, time taking form factor measurements should be minimal. On the right side of the constraint block in Figure 5 the if-and-then statement reads: if equipment upgrades are needed, and there is hardware or software failures, taking form factors is too time intensive. On the left side of the block there are three major causes for the constraint. The logical statements are as follows:

1. Recurrent data acquisition failure occurs if the software needs the computer to run efficiently and the computer is unreliable.
2. BPM motor has a false positive status if there is no beam profile monitor status indication and undesirable effects occur.
3. BPM high gain mode has a potential false positive status if the beam profile monitor high gain status has no feedback and undesirable effects occur.

These three statements produced from the CRT give a basis for finding solutions to the overlap time constraint. The most important being number 1. When the computer fails, it could take a minimum of 10 minutes to reboot the system, load software, and resume. The beam profile monitor is the secondary cause of time wasted because there is no status indicator for any of the BPM motors. Neither is there status for any of the BPM's high gain modes.

Evaporating Cloud

The Evaporating Cloud Technique can now be used to come to logical conclusions on how to act on each of these causes. The Evaporating Cloud takes the CRT and injects assumptions that mitigate or remove conflicts therein (Youngman). Figure 6 shows the Evaporating Cloud with injections to nullify the conflicts. The content of the boxes with "X" marks are no longer considered. Because of the possibility of improvement, it is the logical conclusion make the three main bottlenecks from the CRT into items to act upon.

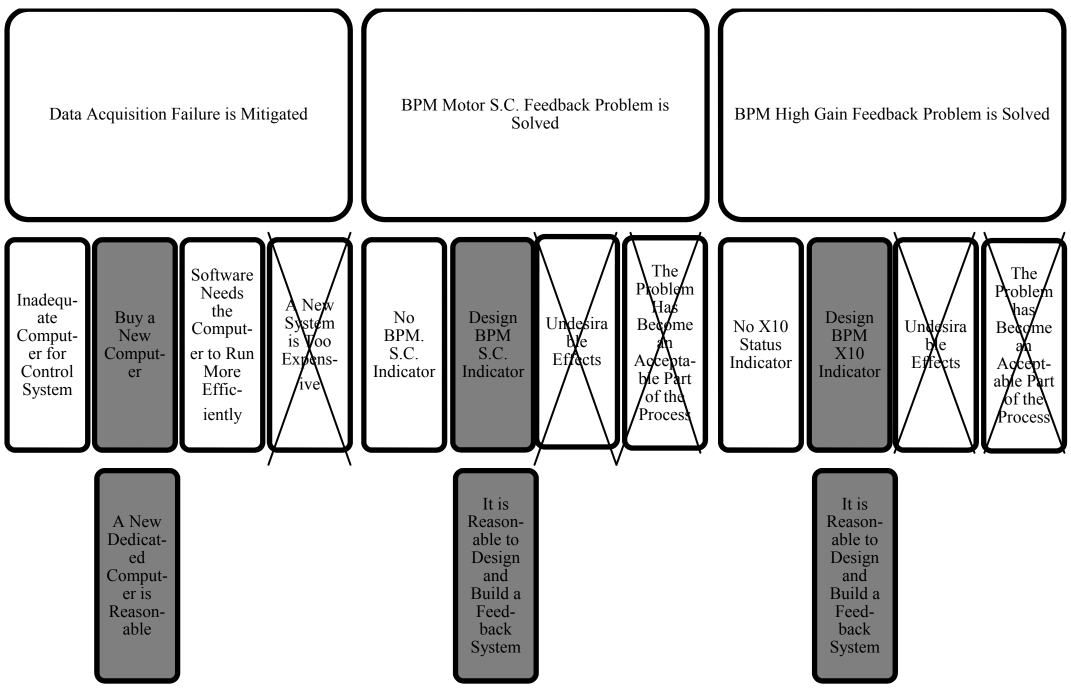

Figure 6. Evaporating Cloud Diagram

The block on the left of Figure 6 has the injection "a new dedicated computer is reasonable." Through logical steps the injected argument that a new computer system is too expensive is nullified (white box with "X"). This conclusion is reached through researching prices and comparing the price to the number of failures. The two arguments are weighed and a conclusion to buy a new computer system is reached (gray box). This justifies the injected argument that buying a new computer system is reasonable. This decision results in the mitigation of data acquisition failure. The same logic of course follows the other two arguments to the right.

Future Reality Tree

The Future Reality Tree (FRT) is a tool similar to the Current Reality Tree. The same logic is used in the CRT with the conflicts removed (Patrick, 2009). From the FRT there is a visual of what the new goals are. Also, there is a logical order that implies what steps need to be taken to reduce form factor measurement time. Figure 7 shows the Future Reality Tree for the Merged Beams Experiment improvement project.

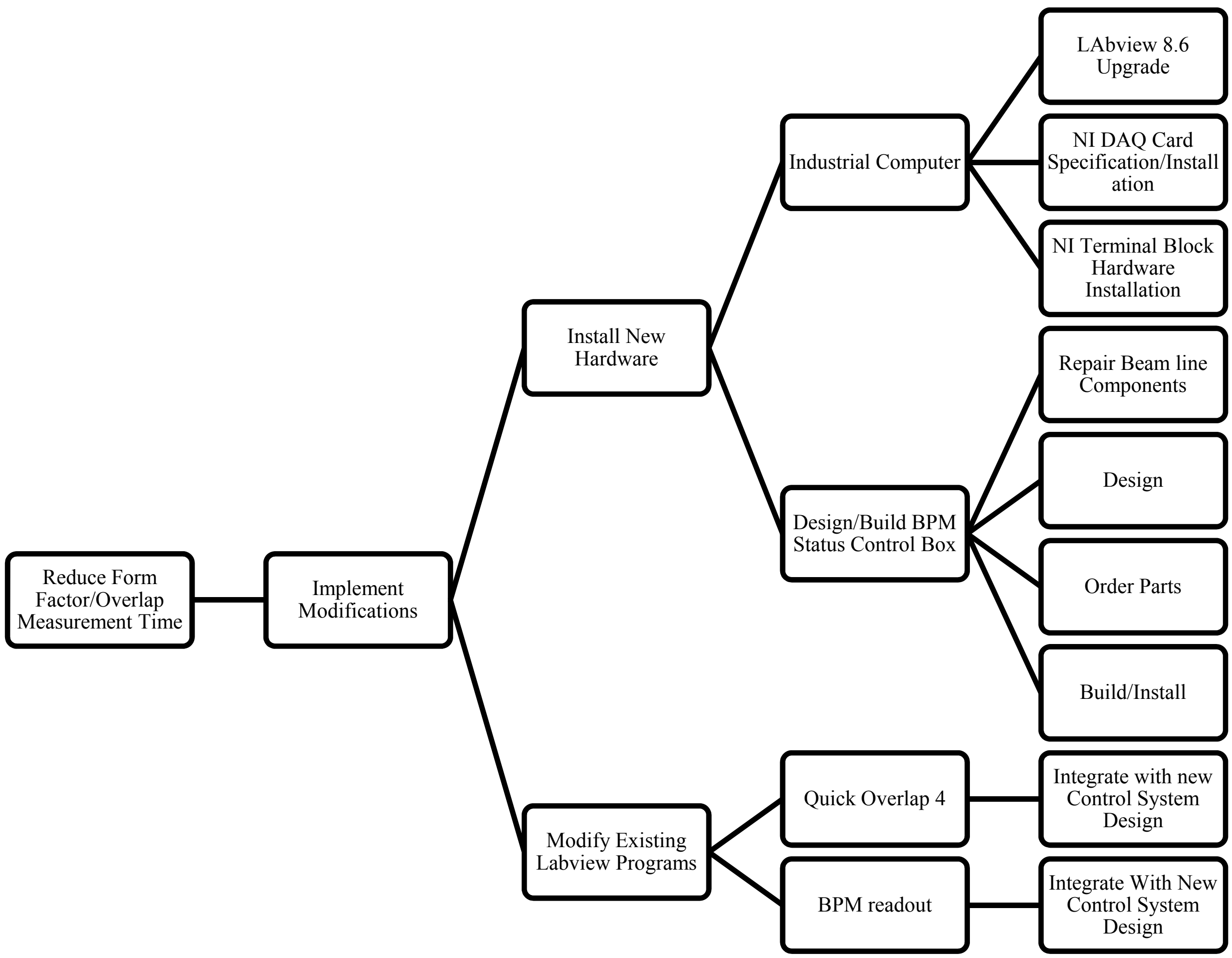

Figure 7. Future Reality Tree Diagram

In Figure 7 the goal of reducing form factor measurement times is shown to the left (top of the hierarchy). The right (Bottom of the hierarchy) states the ground level tasks that need to be achieved in order to graduate to the next level. This next level includes preparation of a new computer and completion of the design and construction of a Beam Profile Monitor control chassis with feedback indicators. This level also represents the beginning of the software development stage. This stage includes the modification of existing Labview used in the MBE (Seely, 2008) and Software used in similar experiments at Columbia University.

These thinking processes (used in TOC) helped the team come to reasonable conclusions once the goal of the Merged Beams Experiment was realized. With clear objectives reducing the time for taking overlap measurements can be achieved.

Details of Improvement Project

Hypothesis: The goal of the MBE improvement project is to test the difference in time between the original process of taking form factors and the modified process. Data points expressed in seconds reflect the time it takes to do a form factor measurement. Therefore, the hypothesis of this project will be expressed as:

Hypothesis: The experiment is successful if the time to take form factor measurements is less.

The null hypothesis will be expressed as:

Null hypothesis: The experiment is not successful if the time to take form factor measurements is neutral to the original measurement.

Involvement

The MBE improvement project in relation to achieving reduction in time for measurement was carried out through the design, construction, and hard work of a dedicated group of people. The project consisted of a group of three.

1. Charles C. Havener: Atomic Physics Oak Ridge National Laboratory
2. Bryan Gross: Instrument Technician, Oak Ridge National Laboratory
3. Samantha M. Strasser: Visiting undergraduate physics major Albion College

Each person in the group had specific tasks to achieve in order to reach the goal. Charles Havener, of course, supervised the project and acquired materials for the experiment. Bryan Gross (the principle author of this thesis) was responsible for the design and construction of the data acquisition system, software design, and design and construction of the BPM control system. Samantha Strasser was responsible for software integration and display format.

Preliminary Data

The time it took to measure form factors was recorded and expressed in seconds. Form factors measurements involve the manipulation of faraday cups, power supplies, and other instruments. Table 1 shows the statistics for the preliminary data. The numbers of interest to this thesis will be the mean, standard deviation, and the variance. These metrics are indicators of the shape, width, and middle of the curve. The table shows the mean to be 918.63 seconds (approximately 15 minutes) with a standard deviation of 540.17 seconds (approximately 9 minutes), and a variance of 291,785.52. The numbers of interest describe the density of the numbers surrounding the mean. If these numbers are reduced significantly from the preliminary data, then the experiment would be considered successful.

Table 1

Pre-Modification Statistics

Form Factor Statistics (Pre-Modification)	
Mean	918.63
Standard Error	131.01
Median	654.00
Standard Deviation	540.17
Sample Variance	291785.52
Kurtosis	1.64
Skewness	1.49
Range	1928.44
Minimum	351.25
Maximum	2279.69
Sum	15616.64
Count	17.00

(Calculated in Microsoft Excel)

A normal distribution (bell curve) displays data clustered around a mean. The data are also distributed less frequently as the data are measured far away from the mean. In a normal curve, 67% of the data is included within the first standard deviation (on both sides of the mean). Within the second standard deviation is 95% of the data. Within the third standard deviation is approximately 99% of the data (Besterfield, 2009). This data when shown in graphical form show the shape of a bell and so it is called a “Bell Curve”.

Figure 8 is a histogram showing the statistics of the preliminary data. The data does not show normalcy in reference to a bell curve. There are five data points that are considered outliers. The reason is a failure during the course of a measurement, causing a time delay. If the outliers were removed, the data would show more normalcy. However the data are used. It is assumed that if the data are taken infinitely, the curve will achieve a normal shape and be distributed evenly around the mean (Besterfield, 2009). However, 17 data points are all that could be achieved within the time constraints.

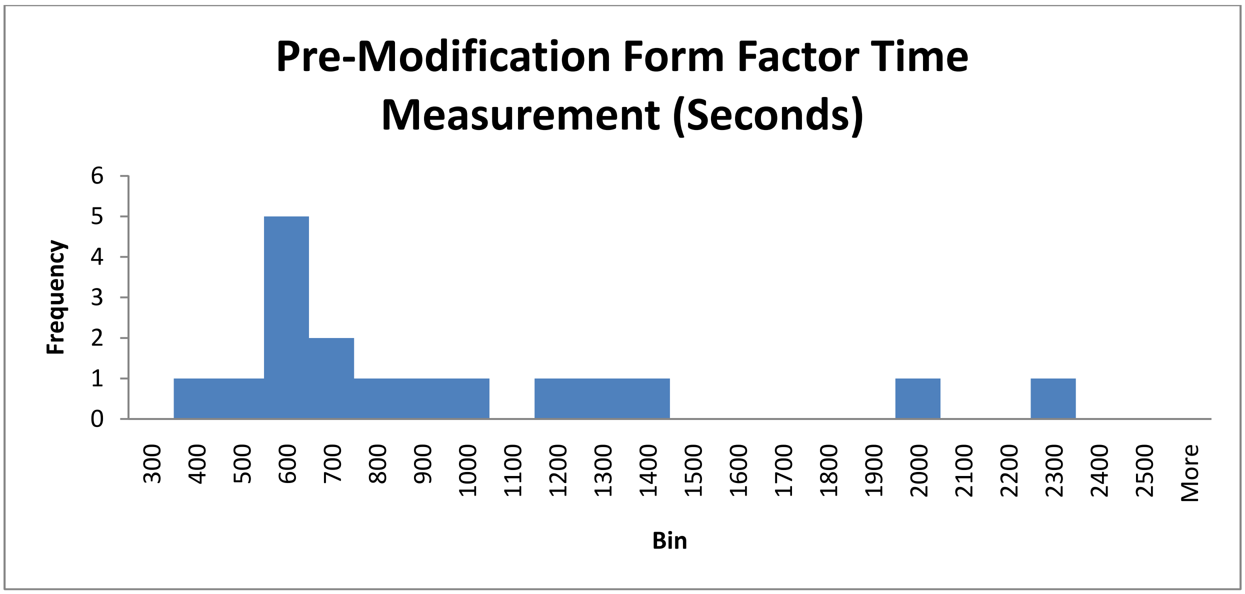

Figure 8. Initial Form Factor Measurement Elapsed Time (Seconds) (Calculated in Microsoft Excel)

These data give a base level measurement for comparison after modifications are made. The next phase of the experiment involves design and construction of certain sections of the merged beams apparatus in order to improve efficiency.

Project Implementation

New Hardware

It was necessary to assess the problems caused by the hardware used in the experiment. The hardware problems were found to be the biggest part of the constraint. Two hardware problems were viewed: the computer system used in the experiment and the lack of centralized BPM control.

Dedicated Computer System

The original computer used to gather the overlap signals was a huge factor in lost time. This computer was extremely dated and the hard drive was almost completely full of programs not dedicated to experimental control. In other words, this was a computer that was not dedicated to the experiment but merely a computer that was used for multiple tasks including the experiment. This computer, being used for tasks that were seemingly beyond what the computer could do, failed often. This required timely restarts of the system. This was especially frustrating for the persons running the experiment who were in the middle of acquiring data. Figure 9 shows the original computer.

Figure 9. To the Left, the Original Computer Used in the Experiment

During the upgrade planning process, agreement on replacement of this computer with a faster and more robust industrial computer came to a consensus. The new computer would be dedicated to the experiment with programs that would only be used for the experiment. Figure 10 shows the new dedicated industrial computer.

Figure 10. The New Industrial Computer Used in the Upgrade

This new computer was specified to have up to 5 PCI slots to be used by the National Instruments cards for data acquisition and instrument control. Also a PCI slot was needed for a SCSI card used to control a motor driven scanner for the final scan of the beam overlap measurements.

<u>Discussion of Computer Software</u>

Charles Havener in recent years sponsored a postdoctoral physicist named Hjalmar Bruhns. While Bruhns was present with the Merged Beams Experiment, he modified the data taking process by writing a Labview software program used to take form factor data. This program communicated with a Tektronix TPS 4034 digital phosphor oscilloscope. The program was written to read the horizontal and vertical cross sections of the beam at two sections and the neutral beam cross section. Figure 11 shows the TPS 4034 instrument used to take data.

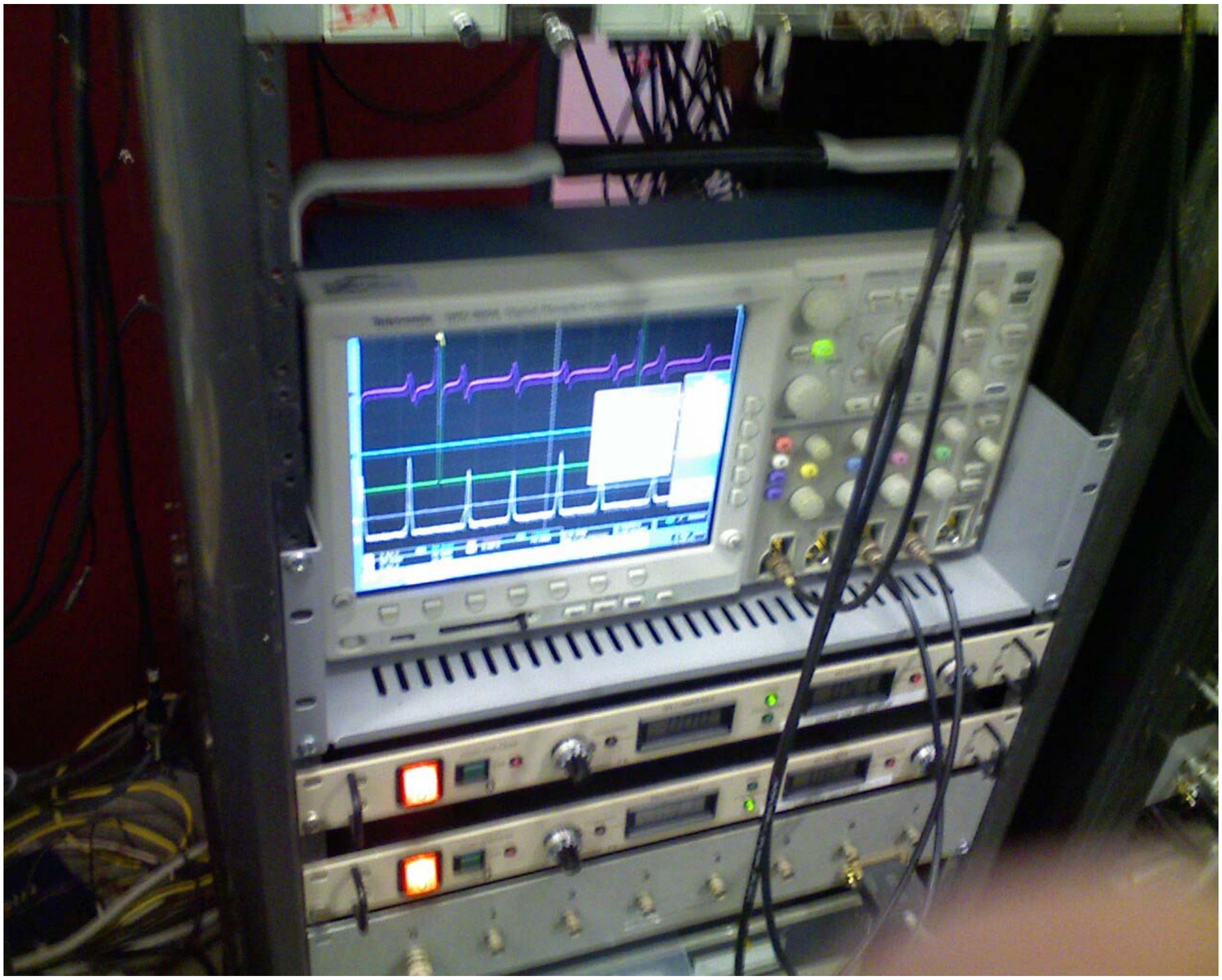

Figure 11. Tektronix DPO 4034 Used to Acquire the Overlap Data

The signals on the oscilloscope originate from Beam Profile Monitor controller modules. These modules control the BPM motor and amplify the signals coming from the beam cross section measurement (National Electrostatics Corporation, 1984). Signal 1 measures the horizontal (H) and vertical (V) upstream. Signal 2 measures the horizontal prime (H') and vertical prime (V') downstream. Also, the fiducial signals are displayed on the oscilloscope as a reference to the proximity of the horizontal and vertical axis of the beam cross section measurement. The neutral beam information is captured and saved on the oscilloscopes available memory.

The program written by Bruhns titled “Quick Overlap” manipulates these signals in such a way that they are expressed in graphical form on the program’s front panel. Figure 12 displays the Quick Overlap front panel. It shows the V and H cross sectional measurements in reference to the neutral beam’s signal (displayed in blue). Under the V and H another graph displays the V’ and H’ cross sectional measurements in reference to the neutral beam’s signal.

This graphical display enables the operator of the apparatus to visualize the V, H, V’, and H’ in reference to the neutral beam. The proximity of the upstream signal to the downstream signal can be inspected and tuned by manipulating the optics. The optics are manipulated through steering power supplies. The supplies apply current to a magnet on the merged beam line. Considering the polarity of the current, the beam is steered in a direction that is deemed satisfactory by the operator. The beam is tuned to match the neutral beam signal through overlapping the neutral beam and the high energy atomic beam. The goal of this exercise is to ensure that both the upstream and downstream overlaps are equivalent in reference to the neutral beam. The graphical display of Quick Overlap (Figure 12) can show the manipulation of the beam in real time. It saves the operator time by allowing the signals to be seen in close proximity (displayed on one screen).

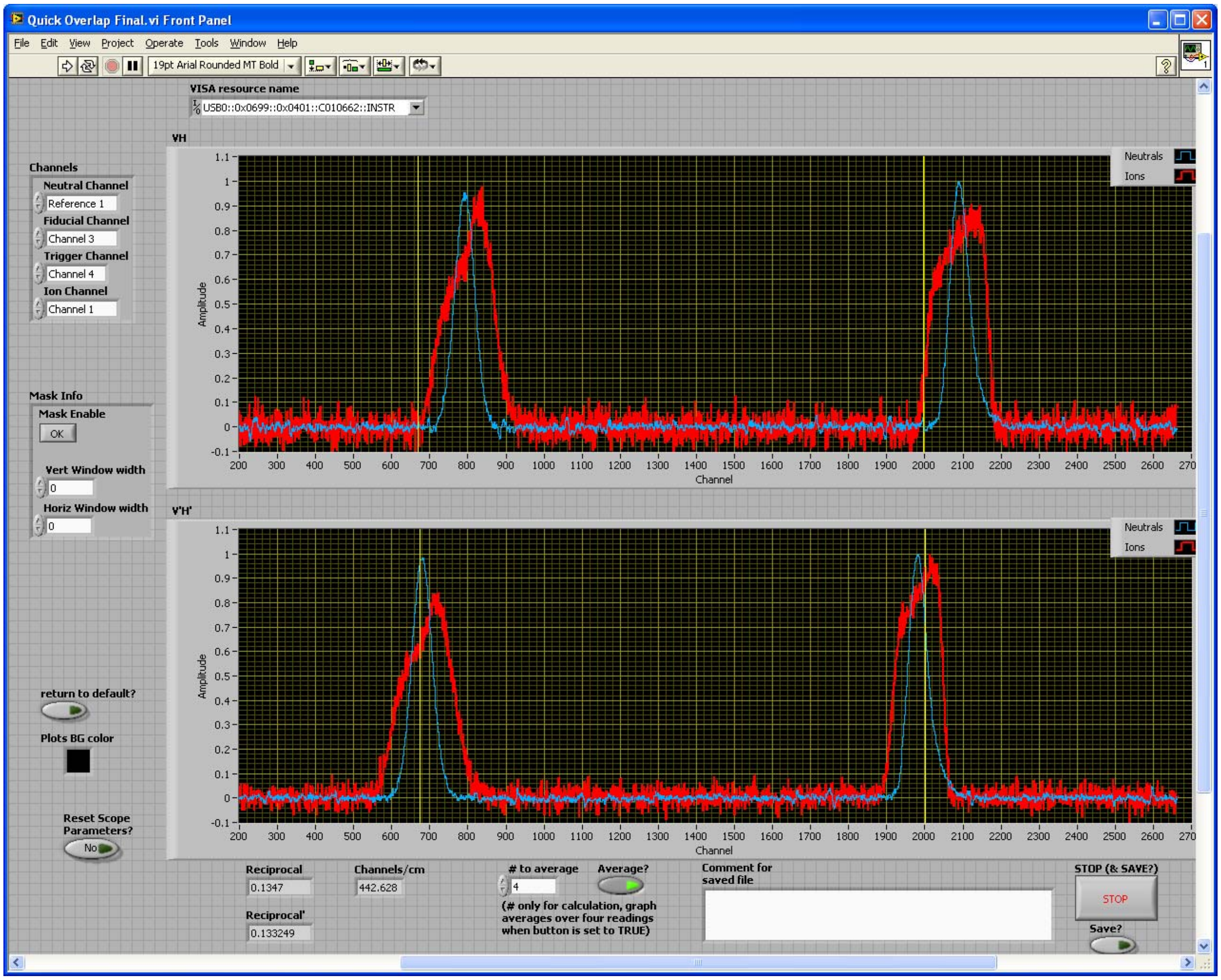

Figure 12. Quick Overlap Labview Program

The Quick overlap program gave a basis for improvement of the Merged Beams Experiment's method of data acquisition and control. The program offered a more efficient way to acquire data and later showed that beam line controls can be manipulated with similar programming through Labview.

After Bruhns left Oak Ridge to pursue similar experiments at Columbia University, He continued writing beam line control software in Labview. Havener found this software to be the "best practice" for the MBE. This helped the team gather specifications for their plans for software, hardware, and beam line floor layout changes.

Bruhns suggested National Instruments Data Acquisition and control card PCI-6225 for acquiring the fiducial and high energy beam signals. This card carried a sufficient number of analog input channels (up to 80). It also had eight digital I/O channels and two analog output channels (NI PCI-6225, 2009). The Oak Ridge team decided on this card that would ultimately read the signals for each of the four beam profile monitors. These BPMs would give two signals each including the fiducial signals and the beam cross section signals.

These signals were passed through a BNC terminal BNC-2090A rack mount connector block, which took the signals and passed them to the PCI-6225 for processing. In addition to passing the BPM signals, the eight DIO channels were available on the front of this terminal block (National Instruments, 2007). The proximity of these terminals eased the availability to pass these signals to the switch card used to energize the solenoids.

The switch card was not suggested in the communication between the Oak Ridge team and Columbia University. This PCI-5521 switch card is capable of switching signals up to 150 Volts RMS (National Instruments, 2005). At this facility, all of the solenoids that control the faraday cups have 115 V AC coils. The switching matrix in the card gave the Oak Ridge team the ability to program an automated control system for these solenoids. Before this event the solenoids were manually actuated by plugging the coils into a power strip. This took the operator out of the seat and to the beam line. This took time away from the experiment. Through automating the faraday cup control, time was saved by programming the faraday cups to actuate in the right sequence, simultaneously, and at the push of a button on a Labview front panel screen.

Beam Profile Monitor Control System

The need for a BPM status feedback system justified the design of a chassis to relieve two problems: BPM motor status control and BPM gain status. Not knowing the status of either could send the operator on a troubleshooting mission. Initially, the BPM motors and high gain control were operated through a NIM module on two different NIM power supplies. This was an easy task, but the lack of feedback left the operators confused when a desired outcome did not happen. For example, if the operator actuated the switch to put the BPM in high gain mode and the signal did not change, the operator would have to investigate the switching module on the NIM bin and perhaps conclude that the BPM was bad. This process was time intensive and took that precious time away from the experiment. Also, the NIM modules used were in two different locations on the control floor. This required the use of two separate NIM power supplies. NIM power supplies sometimes fail, complicating the process. Repair of these supplies is difficult given the parts are no longer available and the in-house technicians are hardly ever available.

The task of building this new system was carried out by the author because of his background in electronics and his involvement in the upgrade project. This task involved designing a board that would send control voltages to the Beam Profile Monitors and monitor the signal through an array of LED indicator lamps. Figure 13 shows a schematic of the circuit. To the left of the diagram, the supply voltage +24V DC enters through J1, a BNC connector. This supplies the voltages for the relay contacts. This voltage level is what is required for the BPM control voltages (National Electrostatics Corporation, 1984). Also to the left, J2, a 9 pin D-Sub connector receives a TTL signal from each of the National Instruments PCI-6225 Digital I/O channels. For example, P0.0 on pin 6 of J2 Biases Q1transistor, which pulls the current of the transistors collector down completing the circuit by switching the transistor to ground (connected to the emitter). This signal actuates the relay on the circuit sending +24 VDC to the motor status control on connector J3 (9 Pin D-sub connector).

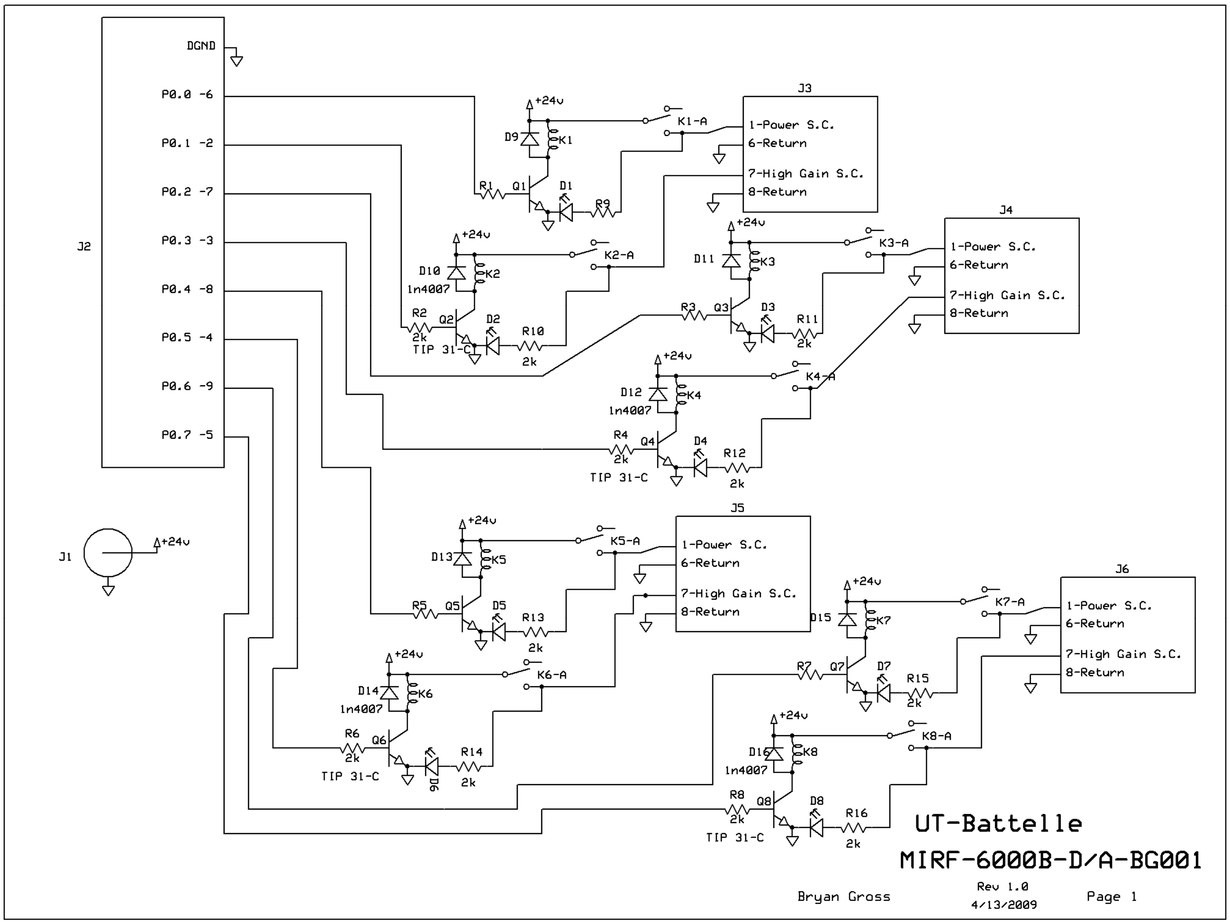

Figure 13. Schematic of BPM Control System

The rest of the circuit is exactly the same for every other signal. In further detail, each TTL signal that goes high on J2 sends a signal to actuate that channel’s transistor that biases and actuates the relay assigned to that channel. The signal that the relay contacts are carrying are sent through the D-Sub connector (J3-J6) connected to the BPM. Figure 14 shows a picture of the PC board in the circuit. Figures 15 and 16 show the front and rear of the enclosure.

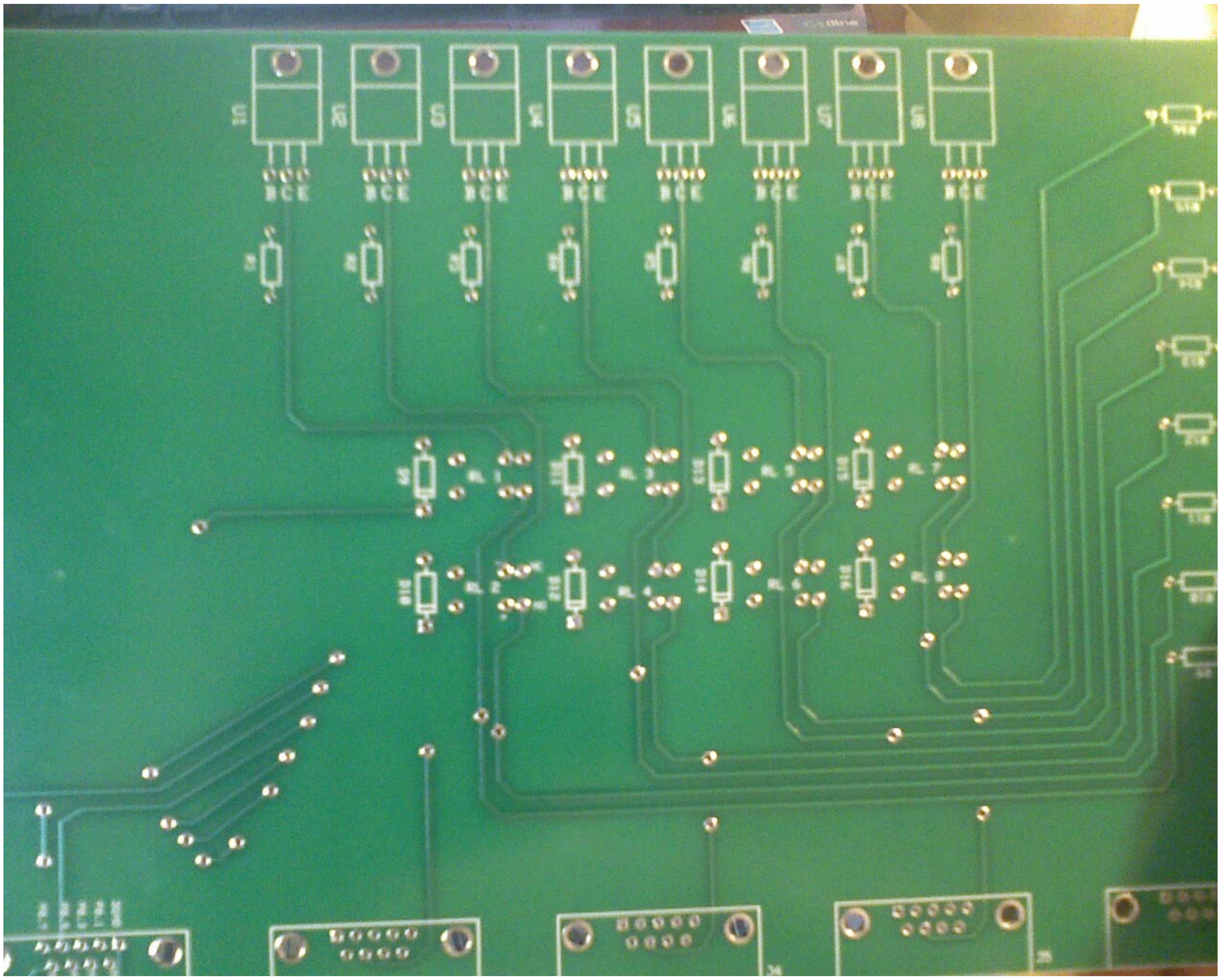

Figure 14. PC Board for BPM Control System

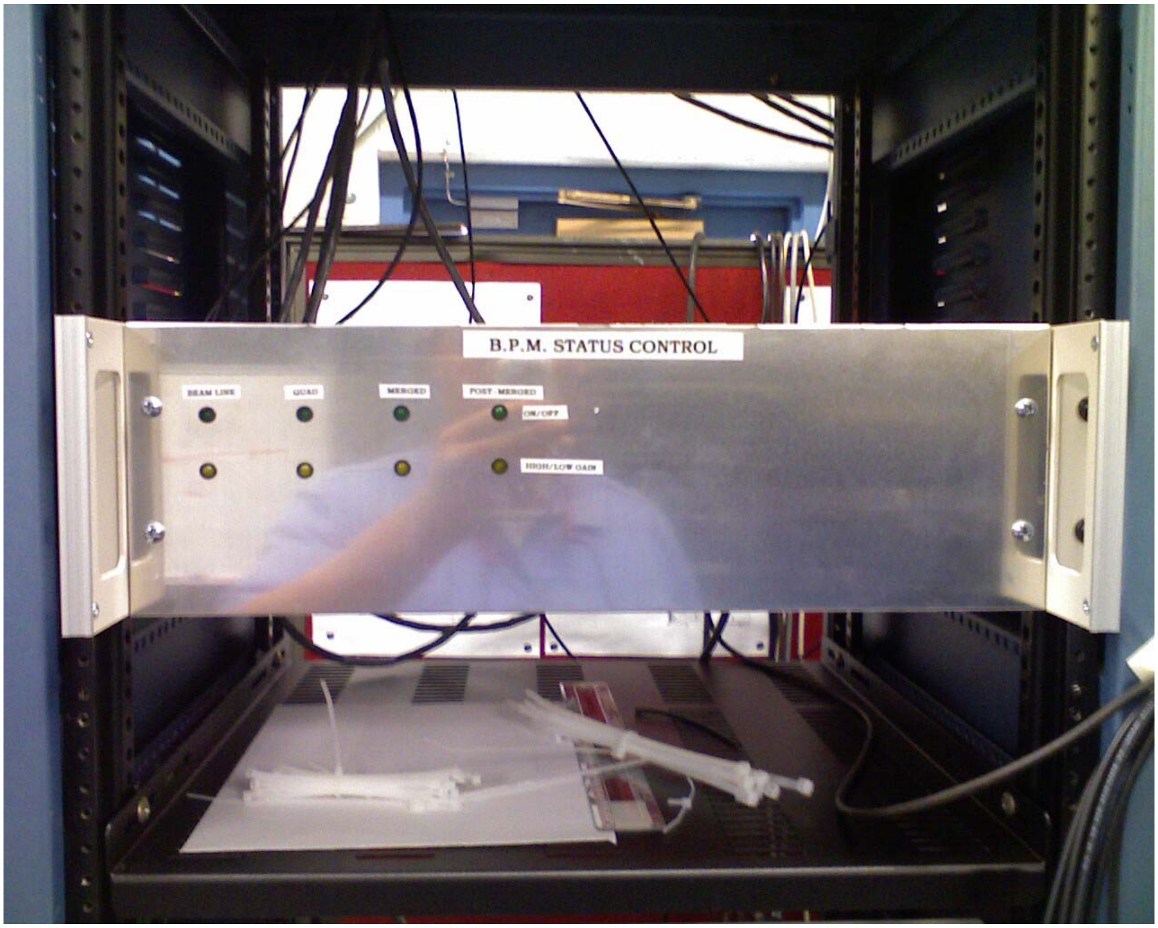

Figure 15. Front Side of BPM Control System

In Figure 15 the green LED indicators show status of the each BPM motor control. The yellow indicators represent the status of each BPM channel's high gain signal. Each LED column represents a BPM module. There are four modules on the beam line.

1. Beam line
2. Quad
3. Merged
4. Post-Merged

Figure 16. Rear View of the BPM Control System

Figure 16 shows connectors J1 through J6. J2-J6 handle the outgoing connections to all four BPMs.

<u>Modify Existing Labview Programs</u>

When construction of the BPM control system and the upgrade from Labview 8.0 to 8.6 was complete, testing for this system was successful. The next phase of the project included software development based on the resources from Columbia University to suit our system needs.

Bruhns was available to answer questions about his software. In fact, the software itself was saturated with commentary on what each section of programming did. This helped the software developer on the Oak Ridge team immensely. Bruhn saved us time by keeping us from "reinventing the wheel."

Several important things were adopted from Bruhn's software. The most remarkable was the signal filtering. Each fiducial marker tells where the BPM wire is in reference to the beam. Bruhns wrote a section of the program that filtered out all of the fiducial markers except for two. These two markers triggered the H and V cross sections of the beam. This section of his program was implemented into the Oak Ridge team's software. Another section of Columbia University's program that was used by the Oak Ridge team was the ability to save the waveforms onto a spreadsheet with the push of a button. The remaining software written by the Oak Ridge Team was written to control instruments.

Instruments controlled through the software were the BPM modules and the Faraday Cup solenoids. These two sections of software helped the experiment save time by controlling these instruments at the push of a button as opposed to actually walking to the instrument and controlling it manually. It also gave the programmer the option of writing code that would run sections of the experiment automatically. Figure 17 shows the front panel of the final version of the control system modification.

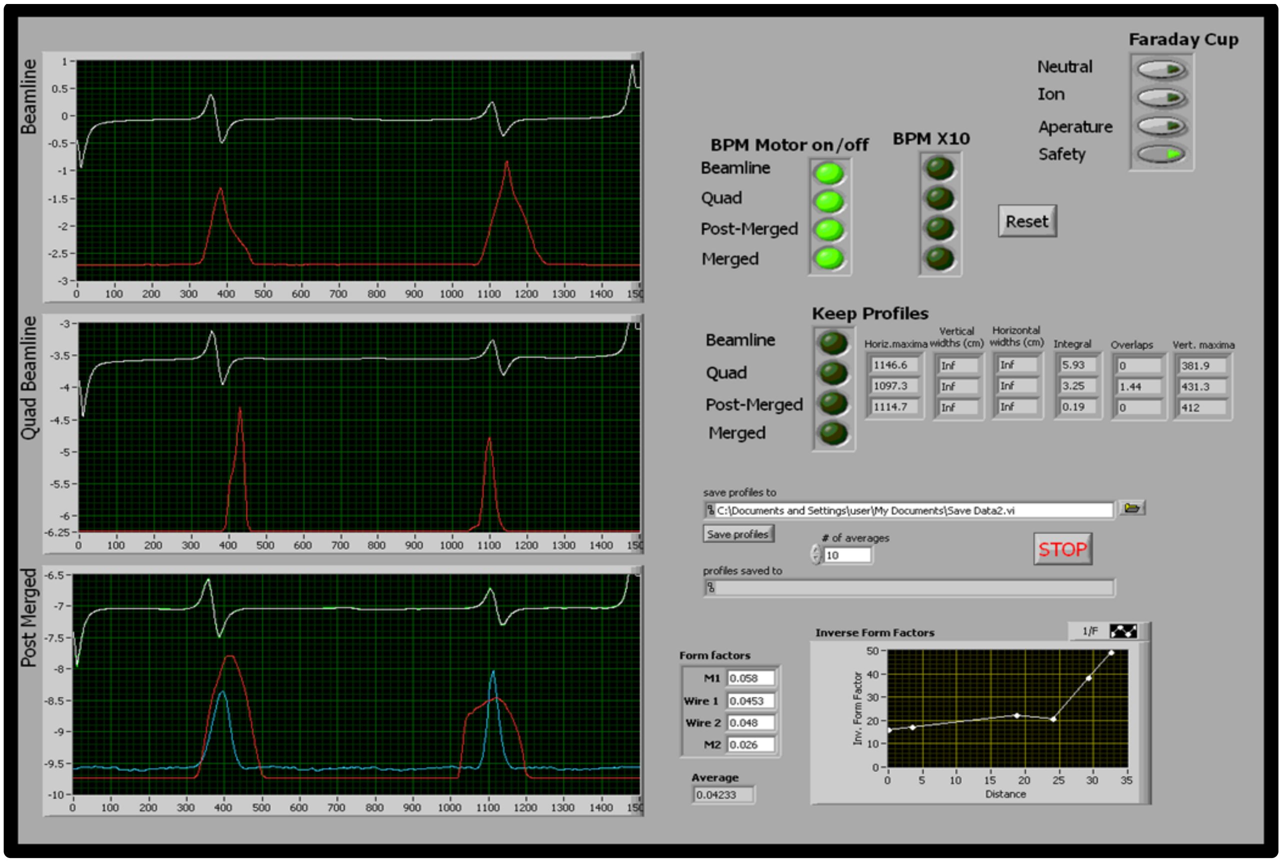

Figure 17. Final Version of the Control System Modification

<u>New Software Uses and Benefits</u>

The Quick Overlap program measures the merged beam path and is still in use. However, upgrading the software where it reads all of the BPMs signals on one screen helped rid the experiment of having to use multiple oscilloscopes. Now, only one oscilloscope is used, the DPO 4034 that the Quick Overlap program interfaces with. The rest of the beam line signals pass through the NI-6225 card on the new computer system.

The new Faraday Cup control allows the operator to pass the beam from one spot on the beam line to another with the push of a button. Before, the FCs were locally and manually actuated. This is a major time saver. Also, the BPM controls allow the user to measure the beam's intensity at four points on the beam line. Before, the BPMs had to be manually controlled.

The ability to record the data at the push of a button gives the operator an advantage. Saving data in an experiment gives the operator the chance to archive information for comparison with other experimental runs.

Post-Modification Data

After the upgrades, form factor times were taken in ten measurements for comparison to the 17 Pre-Modification time measurements. The data we recovered were products of the time allotted for measurement. According to Table 2 the mean time dropped approximately 51% from 918.63 seconds to 453.50 seconds. The Standard Deviation was reduced 93% from 540.17 to 37.57. Also, the Variance was reduced approximately 99.5% from 291,785 to 1,411.39. All of the data in Table 2 overwhelmingly state that the time was reduced significantly. On a histogram (Figure 18) the improvement is obvious. Not only was the time reduced, but the range of data was 95% smaller. The data do support the hypothesis.

Table 2

Post-Modification Statistics

Pre-Modification Data		Post-Modification Data		Change (%)
Mean	918.63	Mean	453.50	50.63
Standard Error	131.01	Standard Error	11.88	90.93
Median	654	Median	450.00	31.19
Standard Deviation	540.17	Standard Deviation	37.57	93.05
Sample Variance	291785.52	Sample Variance	1411.39	99.52
Kurtosis	1.64	Kurtosis	-1.43	187.35
Skewness	1.49	Skewness	0.19	87.51
Range	1928.44	Range	105.00	94.56
Minimum	351.25	Minimum	405.00	-15.30
Maximum	2279.69	Maximum	510.00	77.63
Sum	15616.64	Sum	4535.00	70.96
Count	17	Count	10.00	41.18

(Calculated in Microsoft Excel)

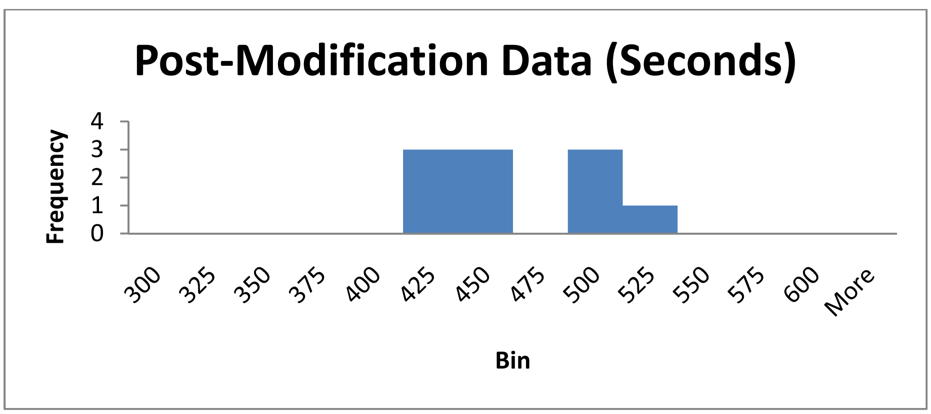

Figure 18. Post Modification Data (Histogram) (Calculated in Microsoft Excel)

The Histogram shows a gap between 450 and 500. It is the author's speculation that the limited number of data points is the reason. If the data points were taken to infinity, then the data would probably take the characteristics of a uniform bell curve. However, one can conclusively state that the modifications reduced the time to take form factor measurements.

CHAPTER 5

CONCLUSIONS AND RECCOMENDATIONS

Conclusion

In summary, this exercise produced positive results that support the hypothesis. The use of Theory of Constraints thinking exercises helped the Oak Ridge team produce good ideas to solve the problem. Inclusion of these ideas into an action plan gave the team a roadmap for change; making it easier to execute a complete plan.

The use of the Current Reality Tree gave the team, in graphical form, an idea of what the problems were and why they existed. The Evaporating Cloud technique inserted arguments into the CRT, nullifying any conflicts that existed. This made it possible to exercise a Future Reality Tree. The FRT gave the team a basic plan for making positive changes.

When everything in the plan was completed, the data gathered represented a significant change from the preliminary information. The analysis of the data, as described in Chapter 4 supported a complete success of the exercise. The time to take form factor measurements was reduced substantially, providing more data of interest to the researchers.

Recommendations

Some of the changes made in the process of carrying out the plan were the product of finding “best practices” in other organizations. For example, when Havener discovered a better way to tackle his software problems at Columbia University, it was decided to implement something similar within his experiment.

It is therefore noteworthy to make some comments about benchmarking exercises that help an organization come to consensus on making plans for change. Appendix A contains a benchmarking guide to find "best practices" for any improvement needed within.

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APPENDICES

Appendix A: Benchmarking Facilitators Guide

Benchmarking Facilitators Guide as written by: Bryan Gross, Yolanda Childs, and Jon Long. Graduate school of Business and Technology East Tennessee State University.

Main Reference:

Brasard, M., & Ritter, D. (1994). The memory jogger Salem, NH: GOAL/QPC.

The purpose of the benchmarking guide section is to give the reader some tools and directions to identify, compare, and possibly implement additional best practices that are applicable to areas that may need improvement. Benchmarking is to be used when key success factors are below expectation. Things that are working better than the norm do not necessarily have to be benchmarked. The key tools for benchmarking include benchmarking gap analysis, brainstorming, affinity diagram, radar chart of key success factor, and . These tools will be helpful in assessing the current state of the key success factor, identifying if it is below the industry average, identifying best practices for this key success factor that may be applicable to your situation, adapting those best practices to your situation, and implementing the best practices to address the gap and move it above the line.

Key Success Factors

Key success factors are typically located in the organization's business plan and must be included in the TNCPE Performance Excellence application. If not identify your organization's key success factors. After identification of the key success factors determine if your organizations' performance in these areas are acceptable or need improvement. For the areas in which improvement is needed, identify a group to address one or more of the areas that need improvement (gaps). This team will begin a systematic process of benchmarking to identify existing best practices that can be implemented to reduce or eliminate the identified gap(s).

Brainstorming

Begin the benchmarking process by the team generating a high volume of ideas to creatively address the gaps. Give each participant a pad of post-it® notes brainstorming Sample text; please delete this before beginning your paper. The Section headings are there to illustrate headings, and to help you see how these headings will appear in the Table of Contents. (Brassard & Ritter, 1994, pp. 19 - 22).

Affinity Diagram

Following the brainstorming session take the information generated and use it to construct an Affinity Diagram. You will do that by following the steps below:

Affinity Diagram

Issue under discussion in full sentence

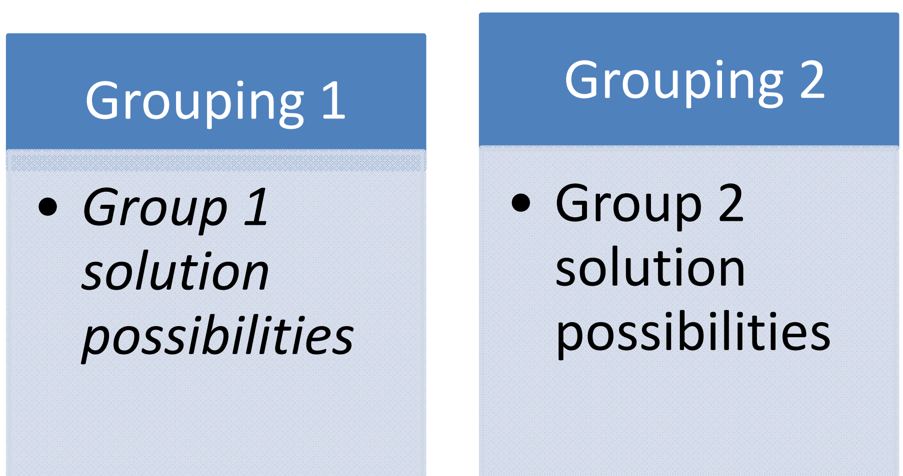


Figure 1 Sample Affinity Diagram

(Brassard & Ritter, 1994, pp. 12 - 18)

Benchmarking Gap Analysis

The Benchmarking Gap Analysis is used to identify the vital few and to know how to focus your benchmarking efforts. A Benchmarking Gap Analysis form below is used to record the data. Information can be recorded on a chart similar to the one in Table 1.

Benchmarking Gap Analysis			
Key Success Factors	As Is	Should Be	Vital Few

Table 1 Sample Benchmarking Gap Analysis

Vital few is defined as the solutions that are most important and have greatest impact/biggest payoff. After the identification of the vital few, these vital few are benchmarked to identify the best practices that may be implemented to reduce or eliminate the gaps.

Internet/Literature Search

An internet and/or literature search is performed to identify other organizations who have successfully addressed the vital few issues and determine if those methods are applicable and adaptable to address the researched vital few issue(s). The best practices are then utilized and or implemented to reduce and/or eliminate the identified gaps.

Radar Chart/Spider Diagram

Radar Chart

The Radar Chart is used to show the key success factor gaps and identify the drivers, the ones that will result in the biggest change. The key success factors or strategic objectives are placed on a circular chart as a spoke. There should be 5 to 10 listed categories taken from the Affinity Diagram. Each key success factor, spoke, is rated with 0 performance being in the center and the maximum performance being at the outer ring, i.e. 10. The gaps are scored by subtracting each gap score from the maximum performance number. The largest difference is the biggest gap, i. e. for A (10 – 1 = 9). This diagram (Brassard & Ritter, 1994, pp. 137 -140). A metric can be added to it and it can be compared with others in the industry.

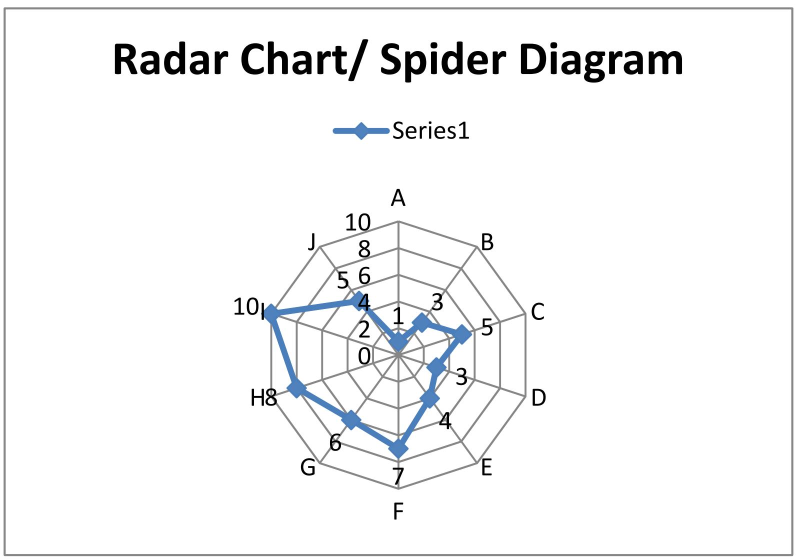


Figure 2. Sample Radar Chart

Interrelationship Diagraph

The Interrelationship Diagraph is used to identify, analyze, and classify cause and effect relationships using a systematic approach that identifies key drivers, bottlenecks, or root causes of the various categories. This tool eliminates the key issues from being biased due to a dominant team member. In this process, concepts/ideas are written on a piece of paper in a circular pattern. Each concept/idea is numbered and pair-wise dependencies are calculated. An outgoing arrow indicates the concept/idea is a driver or root cause. An incoming arrow indicates it is a bottleneck or effect. To use the diagram, one should tally the number of incoming and the number of outgoing arrows for each concept/idea. The concept with the most outgoing arrows is the key driver and the one with the most incoming arrows is key outcome.

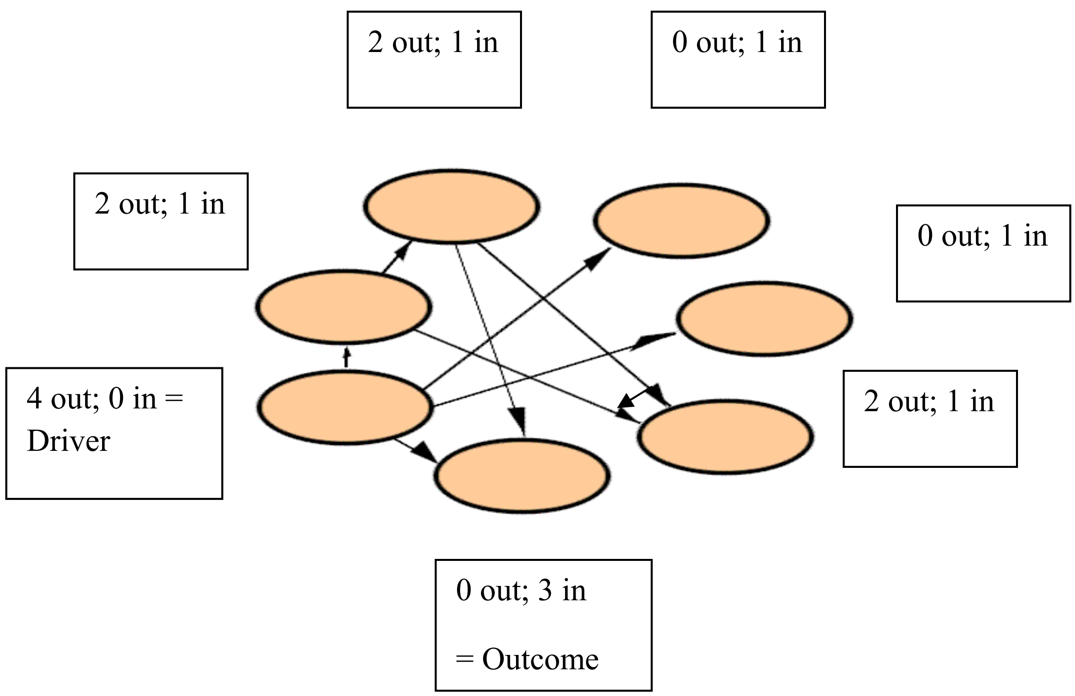


Figure 3. Sample Interrelationship diagraph

Relative Strength Matrix

A relative strength matrix of the relationships matrix can be used to determine and focus on the concepts that have the strongest effect on the greatest number of issues.

Strength of Relationship Matrix

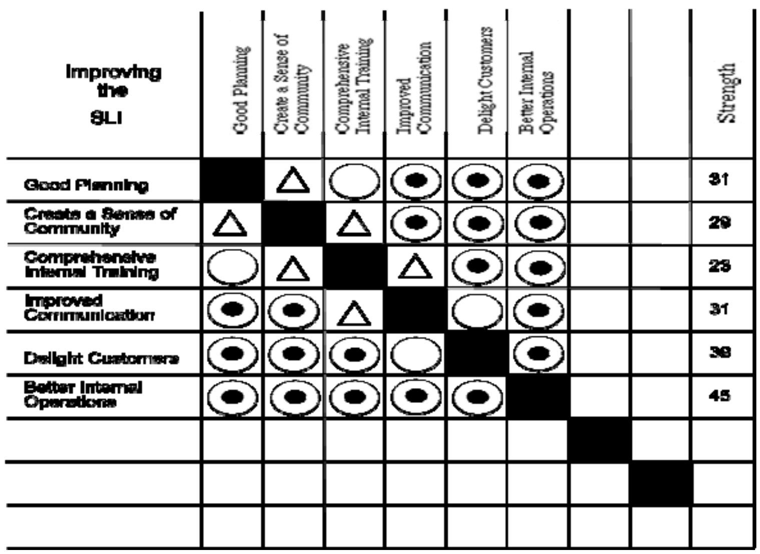


Figure 4. Sample Strength of Relationship Matrix

Relationship Symbols: The most common symbols in matrix analysis are listed below. Generally they are used to indicate:

◉ = High = 9

○ = Medium = 3

△ = Low = 1

The matrix diagram helps the team to identify the correct related factors on which to focus so that they are explored thoroughly. This will assist in making the final decision. The drivers from the Interrelationship Diagraph will be used as the goal in the Tree Diagram.

(Brassard & Ritter, 1994, pp. 76 - 84)

Tree Diagram

The Tree Diagram is used to break down broad goals into smaller detailed actions or tasks that can be done to achieve the goal. To perform this task, a goal statement is selected, a team of 4- 6 or more people are assembled to tackle the goal, brainstorming is done by the team to identify major Tree headings (major sub goals to pursue), the major headings are broken down into more levels by addressing the questions “What needs to be addressed to achieve the goal statement?”(Brassard & Ritter, 1994, p. 159). This process is repeated until assignable tasks are reached or the team reaches the limit to its expertise. Typically Trees are broken out to the fourth level of detail including the overall goal as a level.

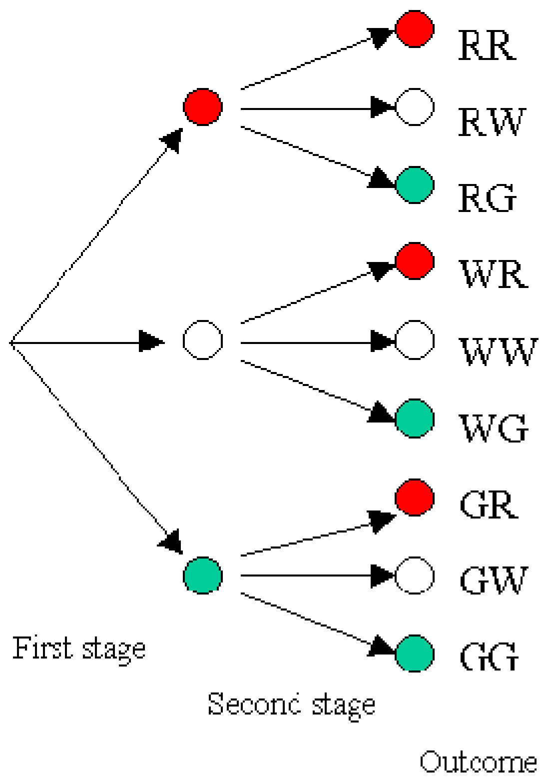


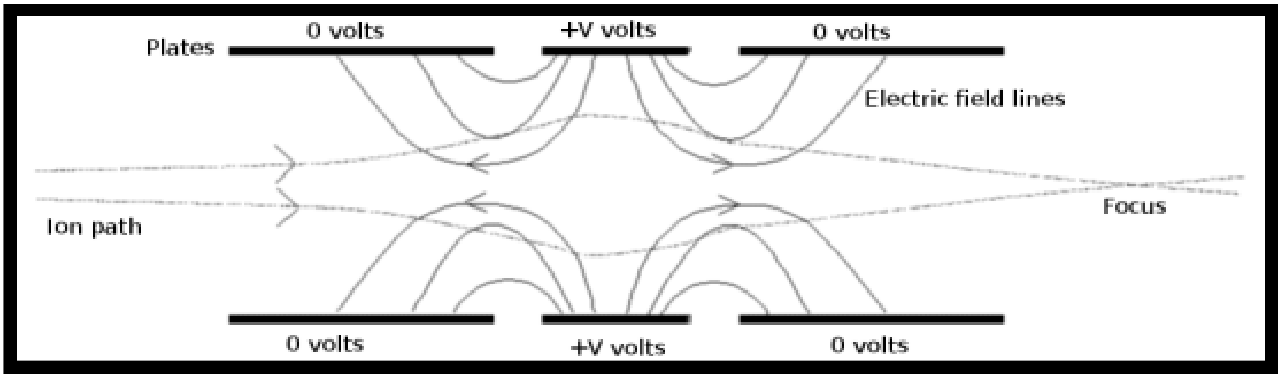
Figure 5. Sample Tree Diagram

(Brassard & Ritter, 1994, p. 156 -164)

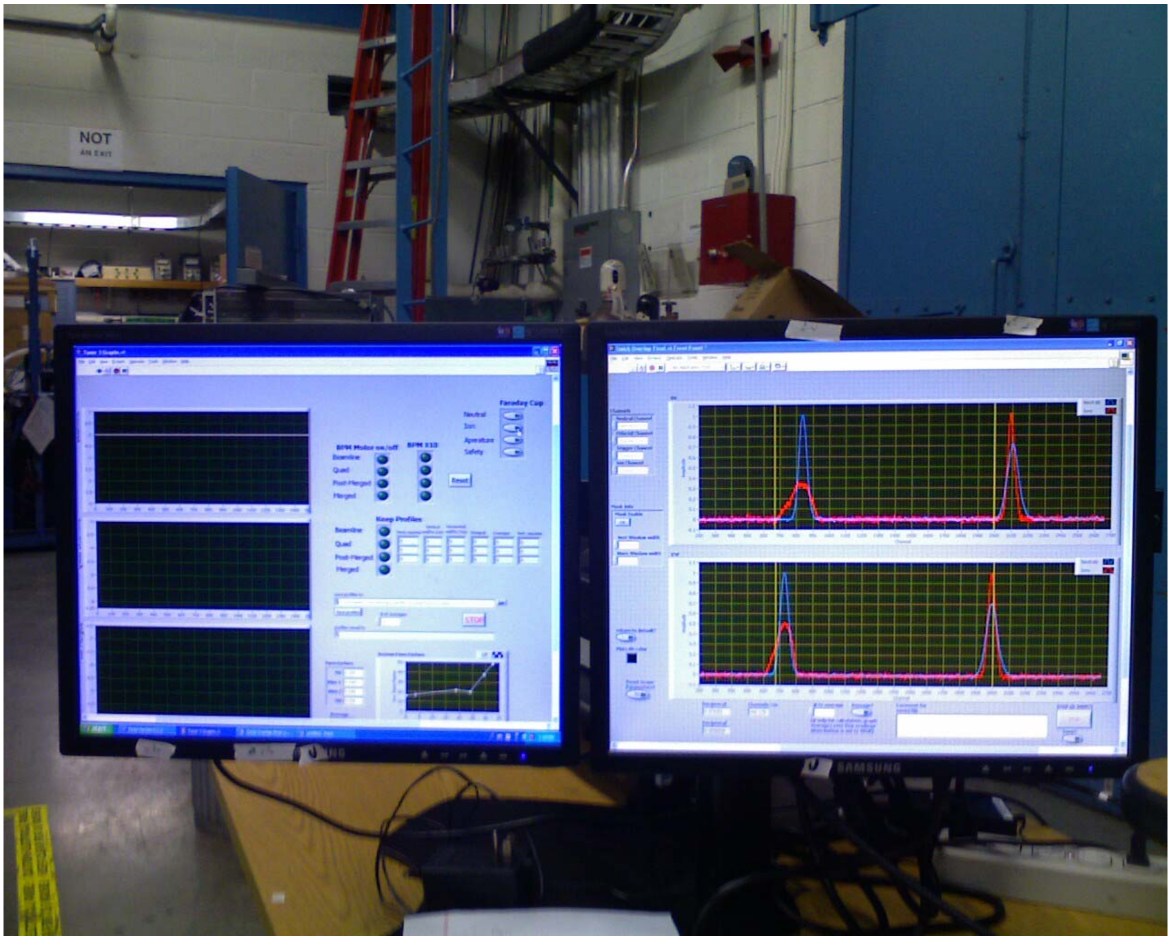
Comparative and Trend Analysis

After the initial literature//internet search and the identification of the key gaps/and or areas needing improvement are completed, these areas are plotted along with the best practices and others in industry over some period of time to identify how they compare (trend) over the specified period of time. This comparison/trend analysis indicates how the areas are performing in comparison to the best in class and others so that an organization will know how it is performing and how much it needs to improve to meet the best in class criteria. This tool is important in determining if an organization is improving continuously or if it has some other type of performance pattern.

Appendix B: Photographs of Experiment Not Included in Body



Einzel Lens Used in Experiment for Beam Optics.

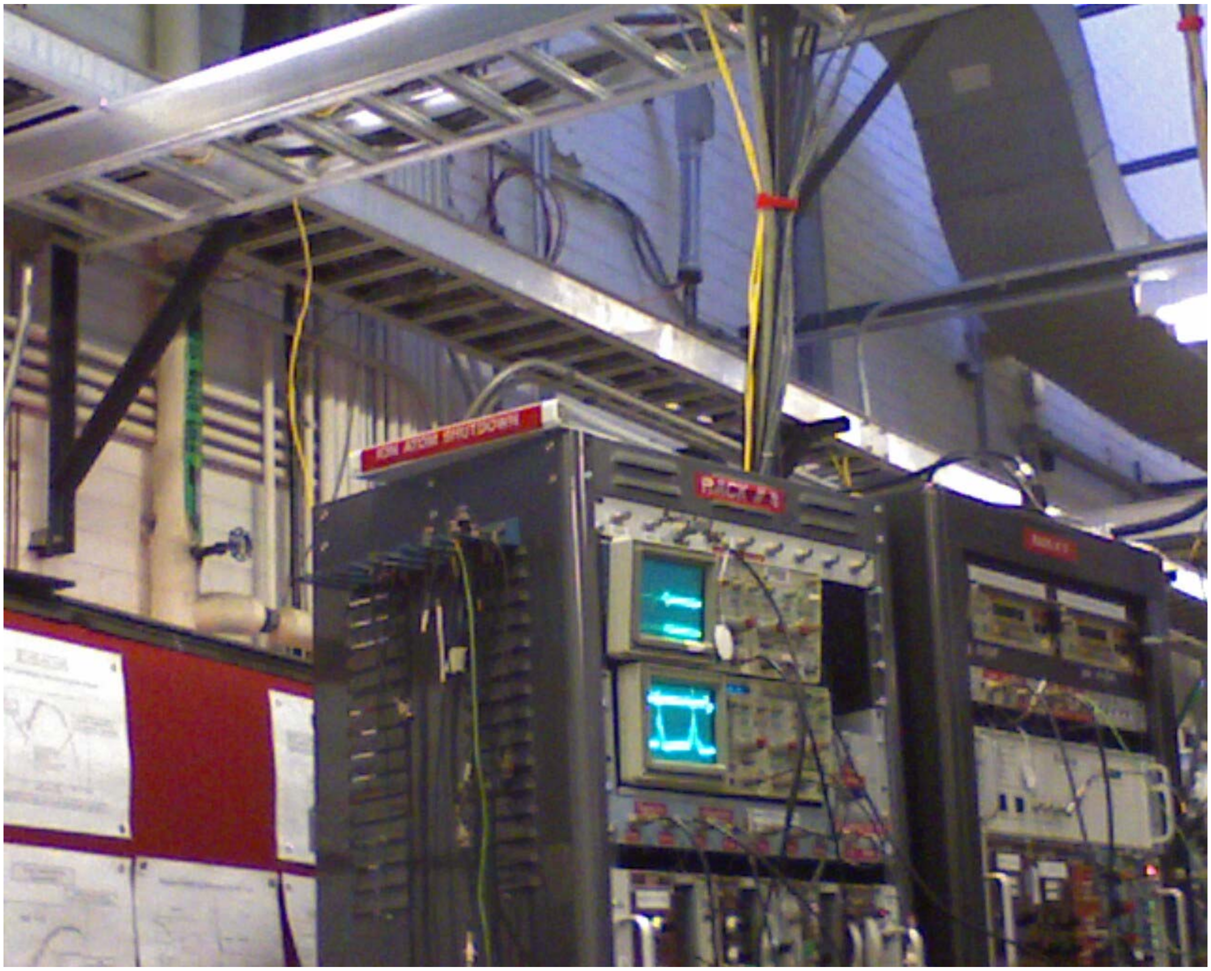


New Program Used Simultaneously with Quick Overlap Program.

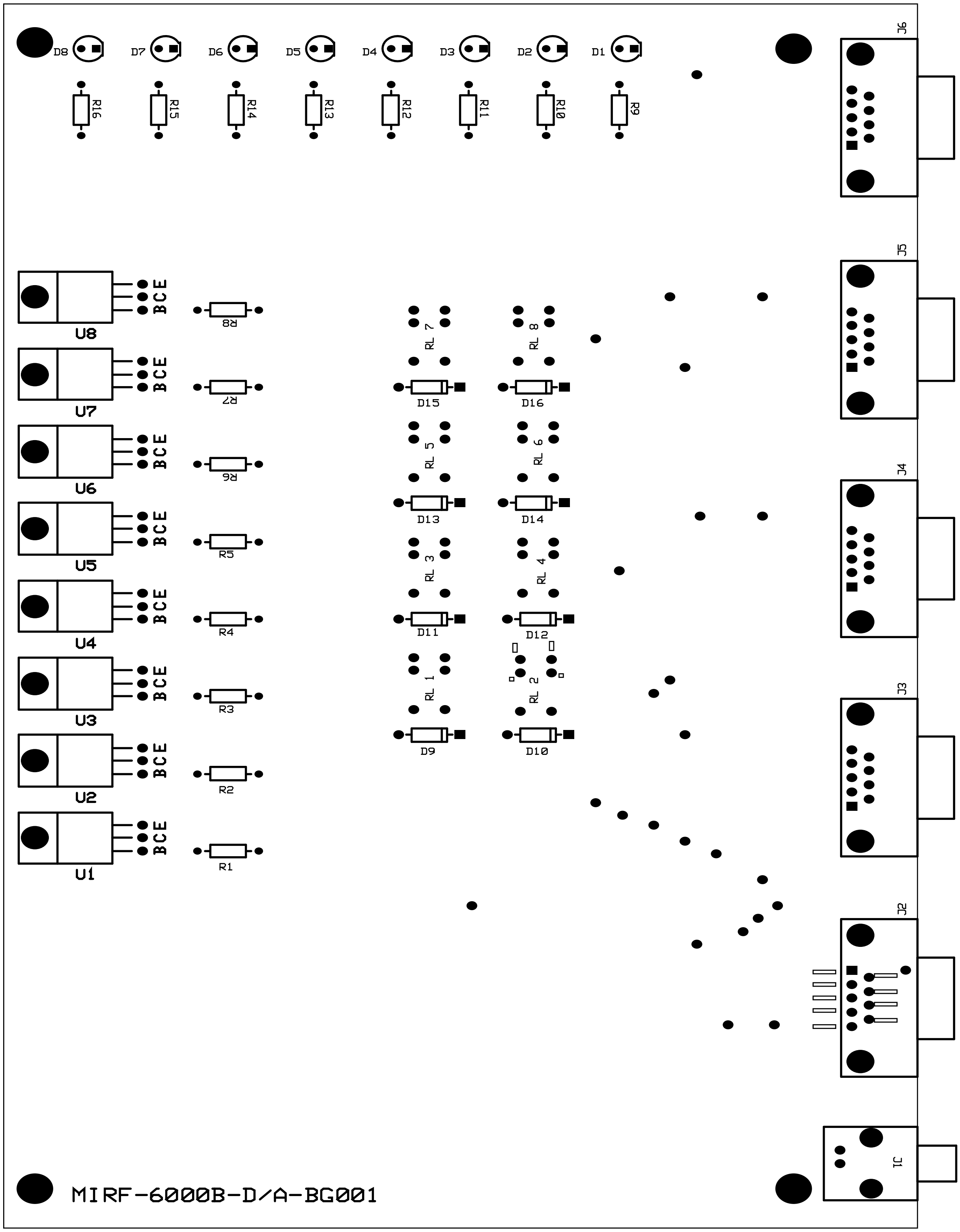
Photograph of Faraday Cup Assembly with Solenoid, (Center Left) and Faraday Cup Shaft (Center)

Equipment Rack Used to House New Equipment.

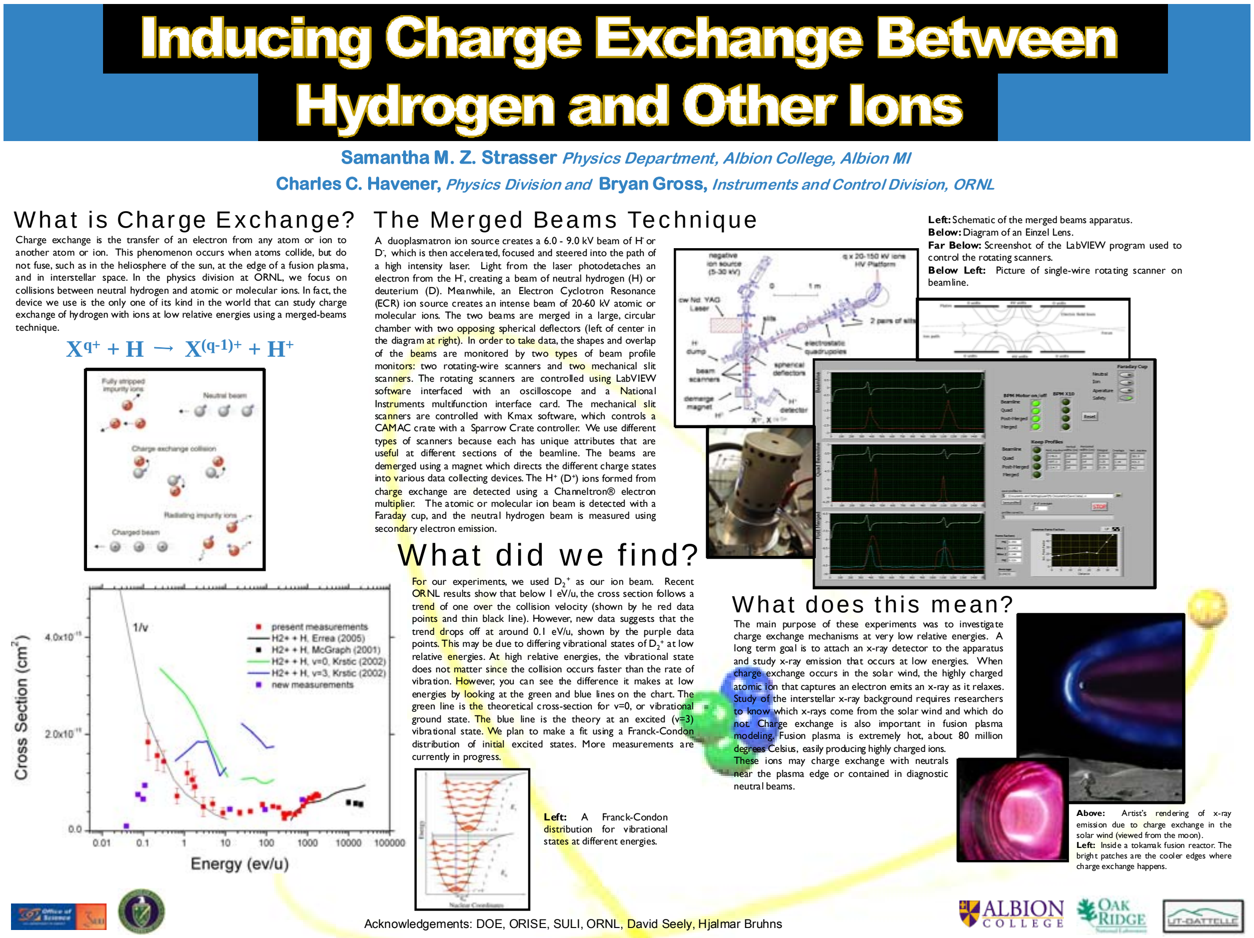
Power supplies, Vacuum guages, and Gauss meters used in the Merged Beams Experiment



2 oscilloscopes that were replaced by the modifications.



Layout of BPM control circuit board (fabricated by Express PCB)



Poster used in presentation of project implementation

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