RECYCLER ELECTRON COOLER DIAGNOSTICS AND INSTRUMENTATION

Courtney Boykin
Electrical Engineering
Alabama Agricultural and Mechanical University
August 5, 2003

Supervisor: Arden Warner
Beams Division

TABLE OF CONTENTS

ABSTRACT

In the Recycler Electron Cooler, a method for monitoring the beam's profile for diagnostic information was desired. To achieve this goal, the idea of using the flying wire was conceived. First, stable PID control of the wire had to be obtained. To perform data acquisition and to control the movement of the flying wire, a LabVIEW application is used. The secondary electron signal will be amplified using an instrumentation amplifier with a bandwidth of 1-5 MHz that can be biased to approximately $\pm$ 100V. The amplified signal will be digitized and analyzed using a Digital Signal Processor to obtain beam profile data and statistics.

INTRODUCTION

BACKGROUND

The Recycler ring is an essential part of the research occurring at Fermilab. The Recycler ring's role is to provide more antiprotons by using it as a high-reliability post-accumulator. It will receive antiprotons from the Accumulator. Electron cooling is required to effectively shrink the phase space dimension of the beam and combat intrabeam scattering during storage. G.I. Budker introduced the idea of electron cooling in 1966 as a way to increase luminosity of p-p and p-pbar colliders. It was first tested in 1974 at the Institute of Nuclear Physics in Novosibirsk, Russia, using proton beams. In 1976, David Cline, Peter McIntyre and Carlo Rubbia proposed using electron cooling for antiproton beams at Fermilab. The goal of the electron cooling group is to use a cold electron beam to cool antiprotons in the twenty meter long straight section of the three kilometer Recycler antiproton storage ring as part of an upgrade scheme designed to increase the luminosity of the Tevatron collider. The electrons will absorb the excess heat of the antiprotons, shrinking the size of the antiproton beam.

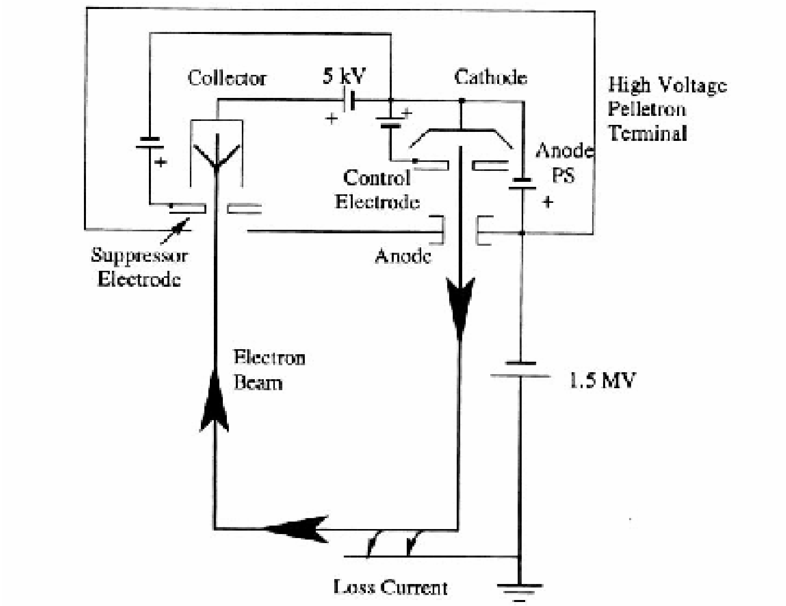
The system parameters of electron cooling can be seen in Chart A.

Chart A: Electron Cooling System Parameters

PARAMETER	VALUE	UNITS
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electrostatic Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	600	G
Cooling Section		
Length	20	m
Solenoid Field	150	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Beam angular speed	≤ 80	μrad

Prior to Fermilab's decision to use electron cooling in the Recycler Ring, electron cooling was used only for low-energy accelerators. However, a low energy accelerator would not have been very useful. Therefore, Fermilab decided to research a method of electron cooling that can be used at high energy. The purpose of this undertaking was to determine the feasibility of using electron cooling for the interaction of a 4.3 MeV, 0.5 A DC electron beam and an 8.9 GeV/c antiproton beam. The only conceivable way to attain the high electron current values desired seemed to be through recirculation of the beam. The electron cooling system will operate in two modes: pulse and DC. In pulse mode the entire beam is lost to ground, making this the method used to tune the beam line. A DC operation with a 0.5 A electron beam is required in electron cooling for the recirculation regime. As can be seen in Figure 1, the electron recirculation system can be represented as a simplified electrical schematic.

Figure 1: Simplified electrical schematic of the electron recirculation system

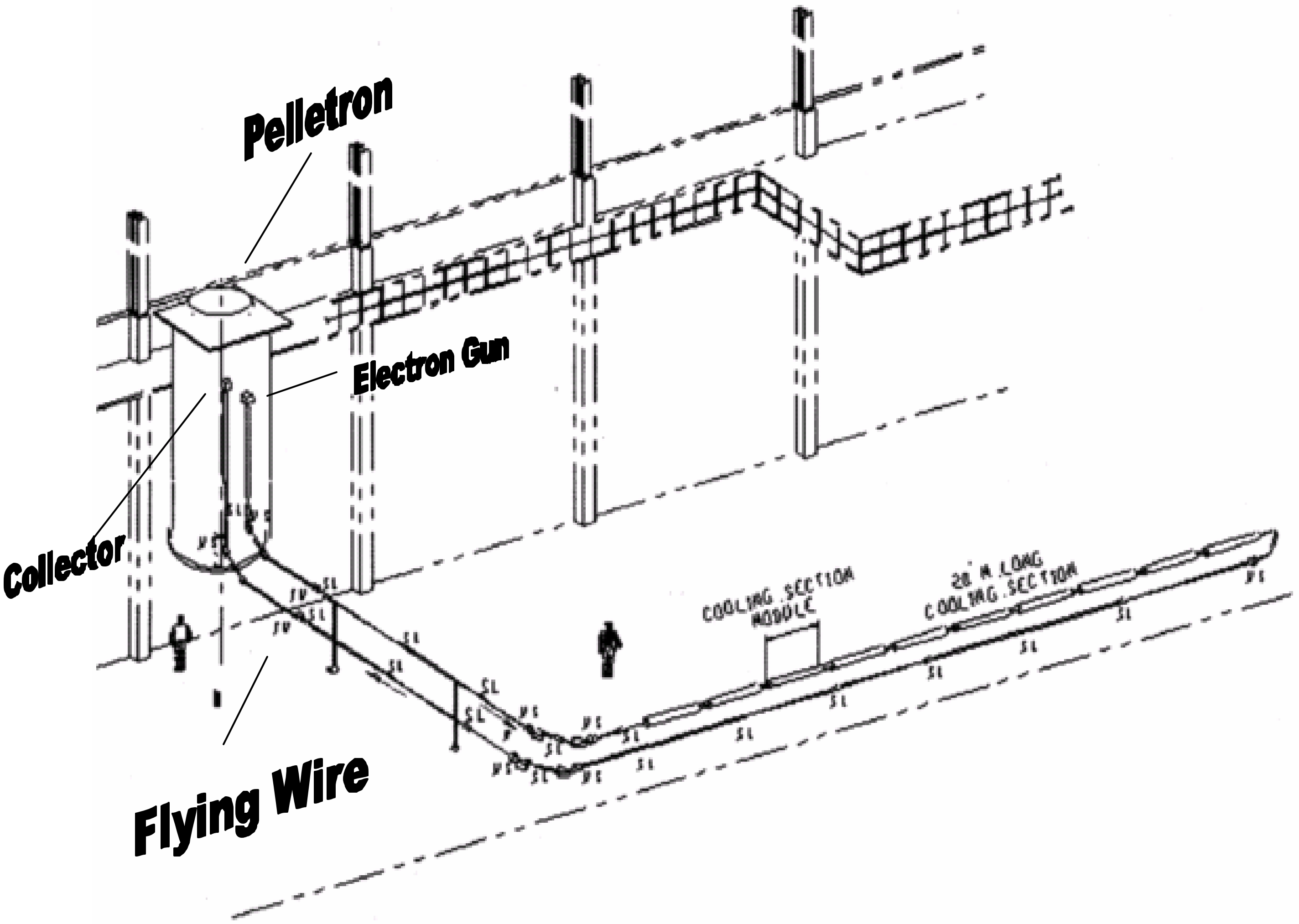


The load on the anode power supply is the loss current. The supply’s current load is usually comparable to the total current loss obtained by a Pelletron voltage regulation circuit. This happens because it is possible for some of the electrons coming from the cathode to be lost to the gun anode.

Pelletron

The Pelletron, a 5MeV electrostatic accelerator, is a type of Van de Graaff generator developed by National Electrostatics Corporation (NEC). It is still the world's only commercially available accelerator, which incorporates an all metal and ceramic acceleration tube with no organic material in the vacuum volume. The NEC Pelletron comes in two configurations: tandem and single-ended. In the single-ended accelerators the high-voltage terminal contains the source and the other end is at ground, where the beam emerges from the Pelletron with energy roughly equivalent to the terminal voltage. The tandem accelerator, unlike the single-ended, has both ends at ground with the high-voltage terminal in the middle. The type that Fermilab is using in electron cooling is the single-ended. The full-scale test facility at wideband building is depicted in Figure 2.

Figure 2: Full-scale test facility at Wideband building



As can be seen in Figure 2, the Pelletron has two tubes and a beam line with a one hundred and eighty degree curve. The electron gun enclosed in the Pelletron is the starting point of the electron beam. The electrons acquire energy by traveling through an electrostatic accelerating tube. The beam is accelerated through the first section of the tube in the Pelletron, passes through the beam line at ground and then returns to the high voltage terminal through the last section of the tube. Traversing the electrostatic field in the opposite direction decelerates the electrons. After the electron beam is decelerated it arrives at the collector where it is prepared to be accelerated again. The Pelletron tank is pressurized with SF_6 gas for insulation and for the cooling of the tank.

Flying Wire

As previously mentioned, the beam is produced in the Pelletron, carried through a path in the cooling section, and returned back to the high voltage terminal, decelerating in the collector. To maintain a high quality beam throughout transfer, several diagnostic devices are used to align and characterize the electron and antiproton beams. As can be seen in Figure 2, there is a 20 m long solenoidal focusing system in the cooling section. The cooling section is made of ten two-meter long modules, each containing a solenoid, correction windings, two BPMs and a pair of scrapers. Scrapers, wire scanners (WS), solenoidal lens (SL), and the flying wire (FW) are among the devices used in electron cooling to measure the profile and position of the beam. The flying wire is used to monitor transverse profiles of recirculated electron beam at the higher beam currents (over 50 μA) that the wire scanners cannot measure. As can be seen in Figure 2, the flying wire is positioned before the bend in the beam line.

As the wire passes through the beam, it is used to observe the profile of the beam and to confirm the beam's optics throughout the transfer beam line. An example of how the flying wire can be used is that if the speed at which the wire passes through the beam and the time it takes the wire to traverse the beam are known, the size of the beam can be determined. The flying wire consists of a piece of carbon with a diameter of 25 μm capable of moving with a speed of up to 8 m/s. The velocity at which the wire traverses the beam is adjustable and is chosen to minimize the heating of the wire and the voltage drop in the accelerator. The wire itself is enclosed inside a Faraday cup made of copper. The cup is designed to capture the secondary electrons that are produced when the wire passes through the beam.

OBJECTIVE

My project focuses on the instrumentation and diagnostics used in electron cooling. High current recirculation of the electron beam with minimal losses is a critical part of the electron cooling process. Diagnostics that do not promote losses or affect recirculation is of importance. It is required that the flying wire device is designed in such a way that it does not cause significant disruption to the process. Stable Proportional-Intergral-Derivative (PID) control of the wire had to be obtained. After that is achieved, the flying wire can be sent through the beam to perform analysis on the beam. To do data acquisition and to control the movement of the flying wire, a LabVIEW application is used. An instrumentation amplifier is used to amplify the secondary electron signal obtained from the flying wire. This signal will eventually be digitized and processed with a Sharc Digital Signal Processor, to get details on the beam's profile and position.

EXPERIMENTAL PROCEDURE

PID LOOP

Proportional-Integral-Derivative (PID) is a control system used for continuous processes. The proportional control is used to correct the deviation of a process. The correction is proportional to the amount of error. The integral control is a type of reset that returns the flow to the original set point. The derivative control produces a corrective signal based on the rate the signal changes. This type of control system was utilized to adjust various parameters to attain smooth movement of the flying wire.

INSTRUMENTATION AMPLIFIER

The project also consisted of assisting in the designing and building of an instrumentation amplifier to replace the previous one used. The characteristics of the amplifier are (a) it must be remotely programmable, (b) it must have a variable gain control, and (c) the bandwidth should be within one to five megahertz. The instrumentation amplifier consists of four separate circuit boards: a ± 100 V power supply, an operational amplifier (op amp) circuit, a ± 15 V and +5 V power supply and a transimpedance amplifier.

The first step taken in building this amplifier was to build the ± 100 V power supply. The power supply is biased at ± 100V because, depending on whether the voltage value is negative or positive, the result can be either a clearing of ions or an attracting of electrons. After this essential power supply was built, work began on the op amp circuit. Both, the op amp circuit and the ± 100 V power supply are connected to chassis ground. Since the op amp circuit was to have a gain of ten, the Burr Brown 3583 operational amplifier was used. After the op amp was chosen, I began assisting with the design of the circuit. After completing the design and beginning the building of the op amp circuit, it was time to think about the ± 15V and +5V power supply. The output of the op amp circuit is the floating ground for the ± 15V and +5V power supply and the transimpedance amplifier. A circuit board for the ± 15V and +5V power supply was found that had already been designed and built before I arrived this summer. All that had to be done for it was to mount it into the chassis that houses all four circuit boards. Before, and even after, the op amp circuit was mounted into the chassis some changes had to be made to its design. Also after the ± 100 V power supply was mounted in the chassis it was realized that this first design was not working very well. Therefore, it had to be redesigned. Finally, it was time to work on the transimpedance amplifier. The work on the transimpedance amplifier had previously been postponed due to a delay in acquiring the prefabricated board for the circuit.

While waiting on the board for the transimpedance amplifier, I worked on the LabVIEW application and on characterizing the old instrumentation amplifier. There were several parameters of the old amplifier that had to be examined to see how it differs from the new amplifier. So, using a precision power supply, an oscilloscope and a multimeter, the old amplifier was characterized. The parameters of the old amplifier were put into a table (shown on pg 11). Finally, after the transimpedance amplifier was finished, it was time to work on characterizing the new instrumentation amplifier. Once again using a precision power supply, a pulse generator, an oscilloscope and a multimeter, the characteristics of the new amplifier were put into a table (shown on pgs 10-11) and graphed (shown on pgs 12-13).

LABVIEW APPLICATION

Acquiring a familiarity with LabVIEW, **Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench, was another aspect of the project. In LabVIEW programs are created with graphics, unlike in traditional programming where programs are written with text. LabVIEW is based on the G programming language. It is a program production and execution system intended mainly for scientists and engineers. LabVIEW offers a powerful graphical production environment for signal acquisition, measurement analysis, and data presentation. With this it is possible to get the flexibility of a programming language without the intricacies of traditional development tools.

The LabVIEW application controls the movement of the flying wire. This application will be able to perform many tasks. The tasks it will be capable of accomplishing include moving the wire at variable speeds, updating wire position using an optical encoder, setting the index, showing the response curve, and generating statistics.

RESULTS

DATA

Table 1: PID Control Loop Parameters

<table>
<tr><td colspan="3">Velocity</td><td>200</td></tr>
<tr><td colspan="3">Acceleration</td><td>100</td></tr>
<tr><td colspan="3">Deceleration</td><td>100</td></tr>
<tr><td colspan="3">S Curve</td><td>1</td></tr>
<tr><td colspan="3">Filter time</td><td>10</td></tr>
<tr><td colspan="3">Distance</td><td>16384</td></tr>
<tr><td colspan="3">Samples</td><td>200</td></tr>
<tr><td colspan="3"></td><td></td></tr>
<tr><td>Proportional Gain, k_p</td><td>Derivative Gain, k_d</td><td>Integral Gain, k_i</td><td>Velocity Gain, k_v</td></tr>
<tr><td>126</td><td>810</td><td>27</td><td>0</td></tr>
<tr><td colspan="3"></td><td></td></tr>
<tr><td colspan="2">Derive Sample</td><td colspan="2">Integration Limit</td></tr>
<tr><td colspan="2">3</td><td colspan="2">1000</td></tr>
</table>

Table 2: Raw data before calibration of amplifier circuit

Vprog	Vfg
0	0.06
1	0.033
2	20.7
3	31
4	41.3
5	51.6
6	62
7	72.3
8	82.6
9	93.6
10	103.1

Table 3: Data after calibration by adjusting resistive values in amplifier circuit

Vprog	Vfg	Vmon
-9.99	-100.3	-10.08
-8.99	-90.3	-9.07
-7.99	-80.3	-8.06
-6.99	-70.3	-7.06
-5.99	-60.3	-6.05
-4.99	-50.2	-5.04
-4	-40.2	-4.03
-3	-30.1	-3.02
-1.999	-20.1	-2.02
-0.998	-10.04	-1.008
0.003	0.033	0.003
1	10.06	1.009
1.999	20.1	2.02
3	30.1	3.02
3.99	40.2	4.03
4.99	50.2	5.04
6	60.3	6.05
6.99	70.3	7.06
7.99	80.3	8.06
8.99	90.3	9.07
9.99	100.3	10.08

Table 4: Characterization of old amplifier

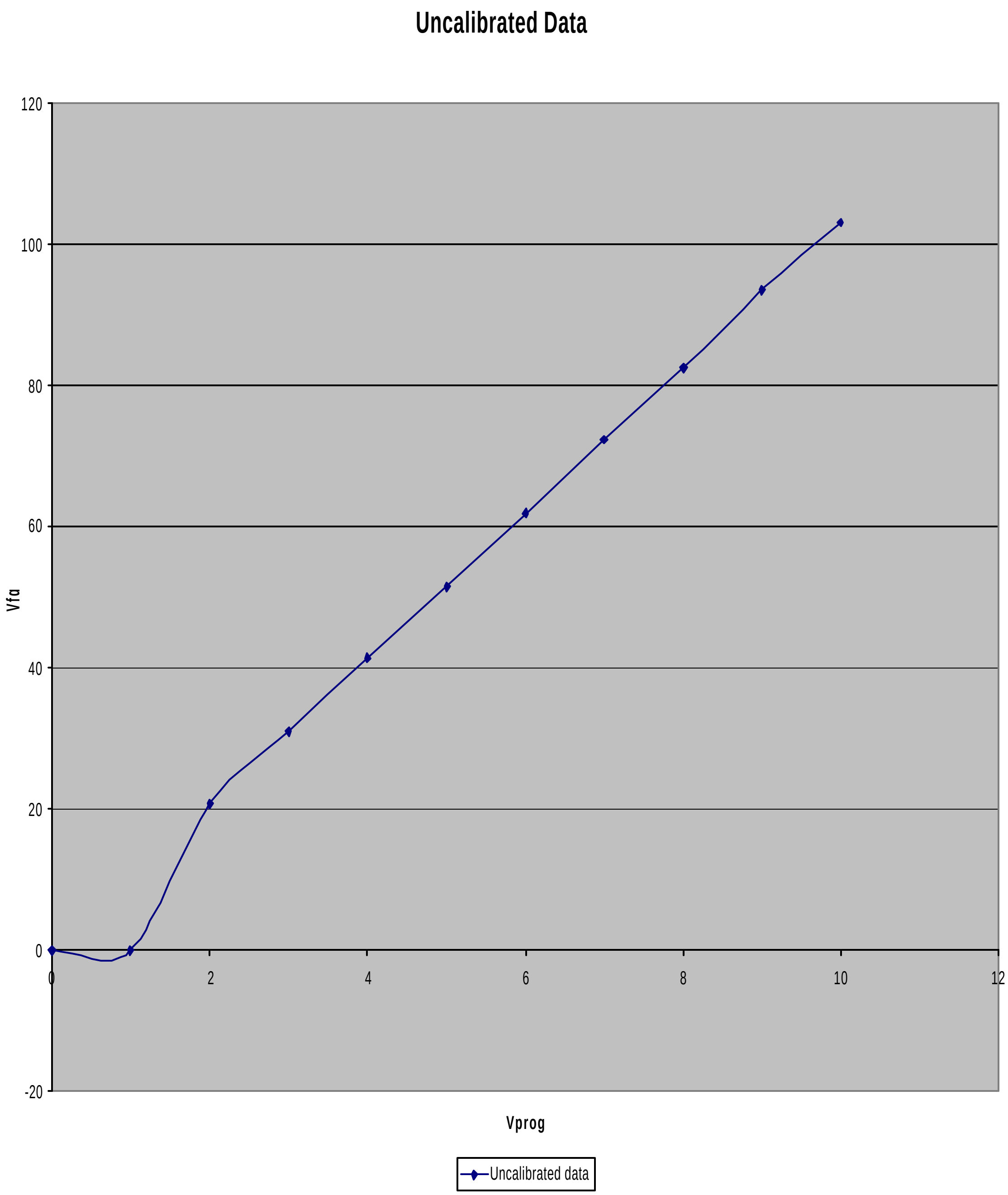
	Max input current	Amplitude	Bandwidth
Gain of 1	1 mA	100 mV	62.5 kHz
Gain of 10	10 µA	10 V	62.5 kHz

Table 5: Comparison of characteristics of old and new amplifier

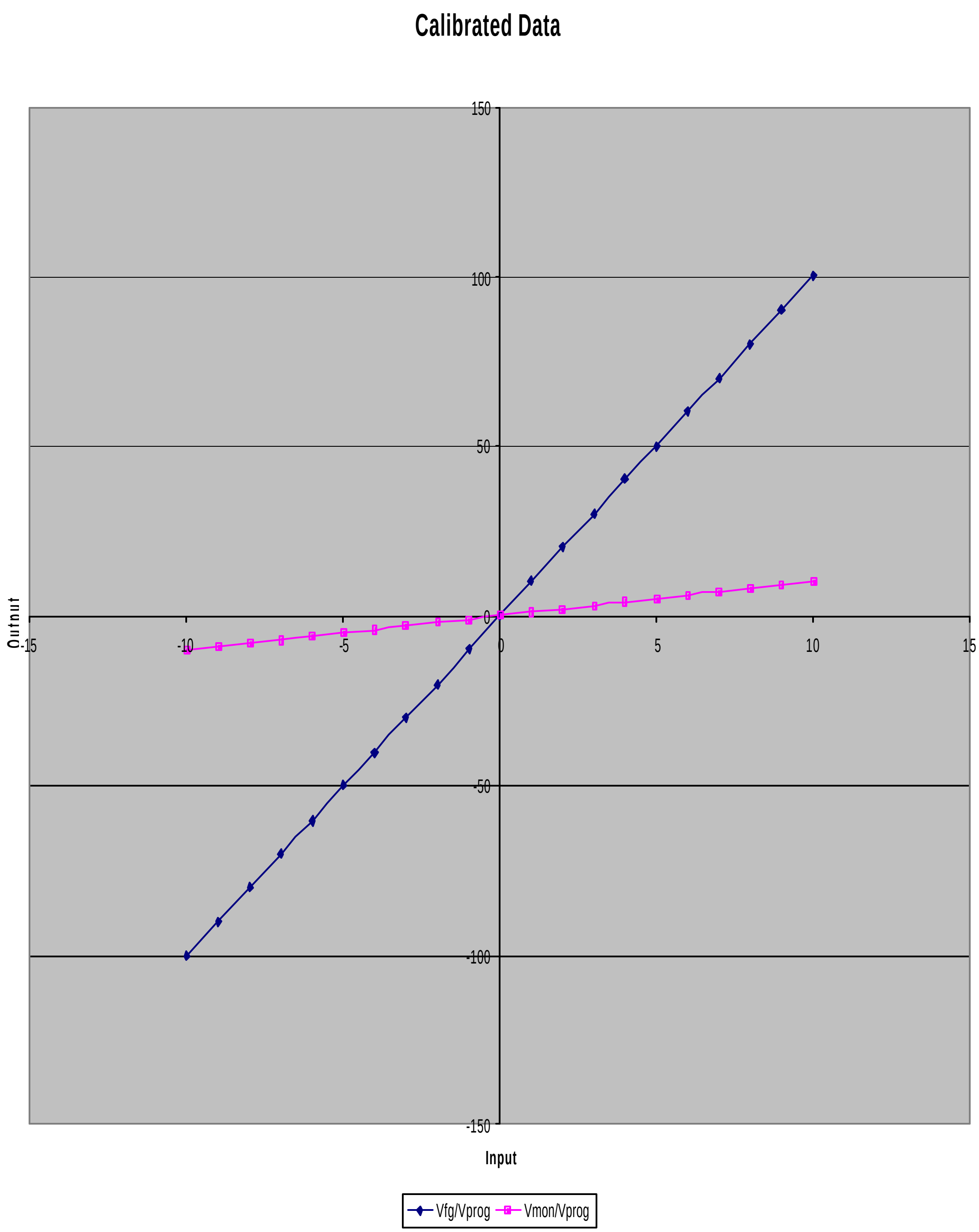
Parameter	Max input current	Bandwidth
OLD AMPLIFIER		
Gain of 1	1mA	62.5 kHz
Gain of 10	10 µA	62.5 kHz
NEW AMPLIFIER		
Gain of 1	1mA	5 MHz
Gain of 10	100 µA	1 MHz

ILLUSTRATIONS

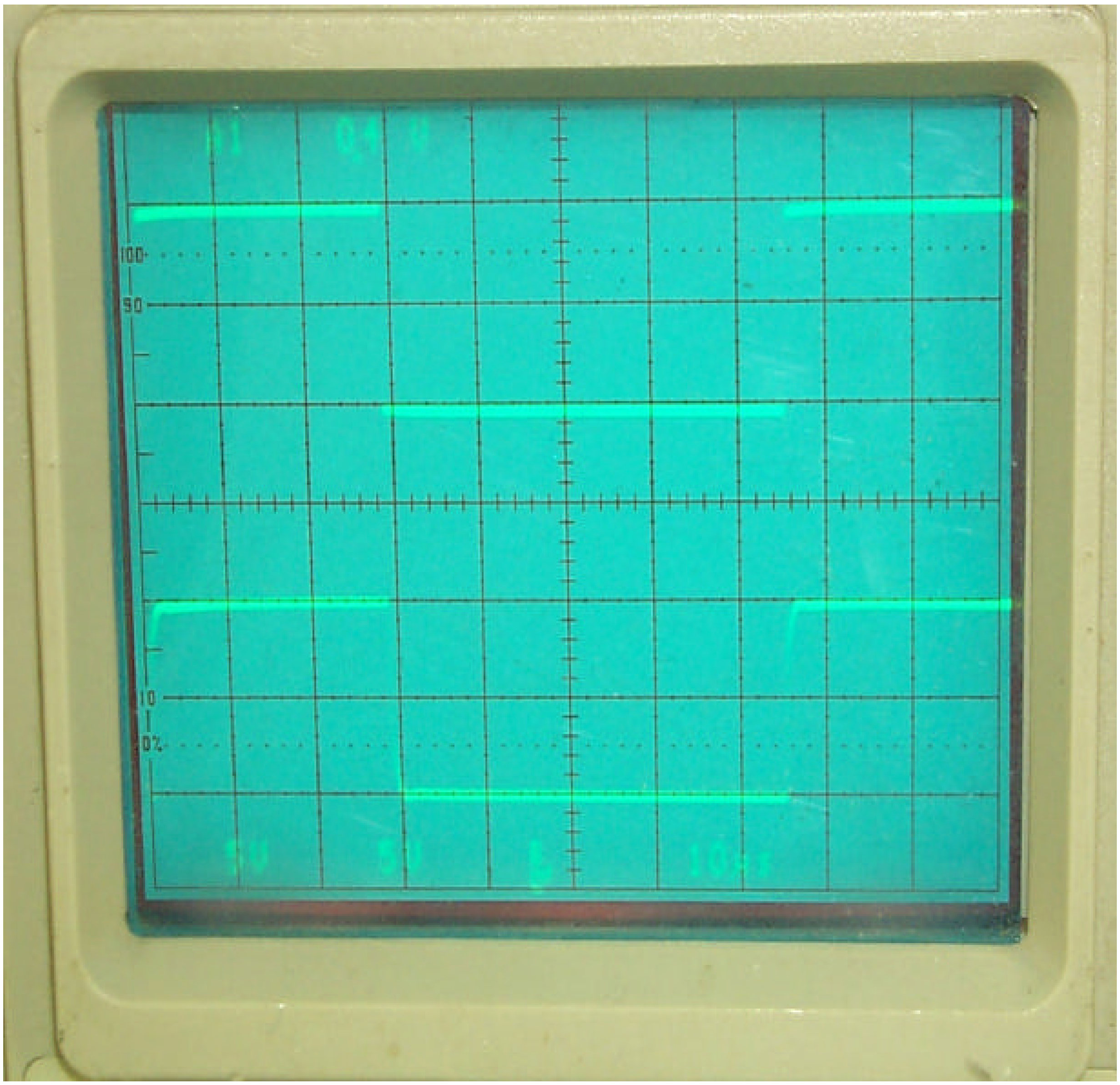
Graph 1: Raw data before calibration of amplifier circuit



Graph 2: Data after calibration by adjusting resistive values in amplifier circuit



Graph 3: Shows oscilloscope representation of the output directly from the pulse generator compared to the output obtained after the signal has been put into the instrumentation amplifier



DISCUSSION

PID LOOP

The values needed to obtain stable PID control can be seen in Table 1 (shown on pg 10). These values are the various parameters needed to obtain smooth movement of the flying wire. The parameters that had to be examined to obtain stable PID control are the velocity, the acceleration, the deceleration, the s curve, the filter time, the distance and the number of samples. Also the PID system helped determine the values of proportional gain, derivative gain, integral gain, and velocity gain.

INSTRUMENTAION AMPLIFIER

The first step taken in testing the new instrumentation amplifier was to obtain a plot of the uncalibrated circuit. To attain Graph 1 (shown on pg 12), which depicts the uncalibrated circuit, the programmable voltage value (V_{prog}) and the voltage value at the floating ground (V_{fg}) were determined. The voltage values obtained from the uncalibrated circuit can be seen in Table 2 (shown on pg 10). Since the plot of the uncalibrated circuit shows that at the lower voltages the circuit did not performed as desired, the decision could be made on how to adjust the resistive values to increase the circuit's performance. The results of the calibrated circuit can be seen in Graph 2 (shown on pg 13), which depicts the plot of the comparison of V_{fg} / V_{prog} and V_{mon} / V_{prog}, where V_{mon} shows the monitor voltage. It can be seen here that the resulting graph is more linear than the previous graph. The voltage values obtained from the calibrated circuit can be seen in Table 3 (shown on pg 11). Graph 3 (shown on pg 14) illustrates the comparison between a signal feed to an oscilloscope directly from a pulse generator and the waveform obtained after the signal had been put into the instrumentation amplifier. As can be seen in Graph 3, the output from the instrumentation amplifier (the lower waveform) closely tracks the output of the pulse generator (the upper waveform).

To better understand how the new amplifier is to differ from the previous amplifier, the old amplifier had to be characterized. The parameters of the old amplifier can be seen in Table 4 (shown on pg 11). After the previous amplifier was completely characterized, its parameters were compared with the parameters of the new amplifier. The comparison of some characteristics of the old and new amplifier can be seen in Table 5 (shown on pg 11).

LABVIEW APPLICATION

The application is able to load the specifications of the motor to the motion control card. Using the specifications of acceleration and velocity for the flying of the wire, the motor can be initialized. Also, a single axis move can be completed using a user-specified position on a single axis while using user-specified parameters. After the motion has stopped, the position is checked. Work on obtaining a preliminary estimate of the profile is still in progress.

CONCLUSIONS

Stable PID control of the wire has been obtained. The characteristics that the instrumentation amplifier currently possesses have been examined. The instrumentation amplifier is mostly complete. Upcoming plans for the amplifier include the addition of fiber optics or some alternative method if a suitable one can be found. The LabVIEW application still requires some additional coding but should soon be complete.

REFERENCES

Travis, Jeffrey and Lisa K. Wells. LabVIEW for Everyone. Prentice Hall. Upper Saddle River, NJ, 1997.

Hill, Winfield and Paul Horowitz. The Art of Electronics. Cambridge University Press. NewYork, NY,1989.

Fermilab Electron Cooling Project: http://www-ap.fnal.gov/ecool/

National Electrostatics Corporation (NEC): http://www.pelletron.com

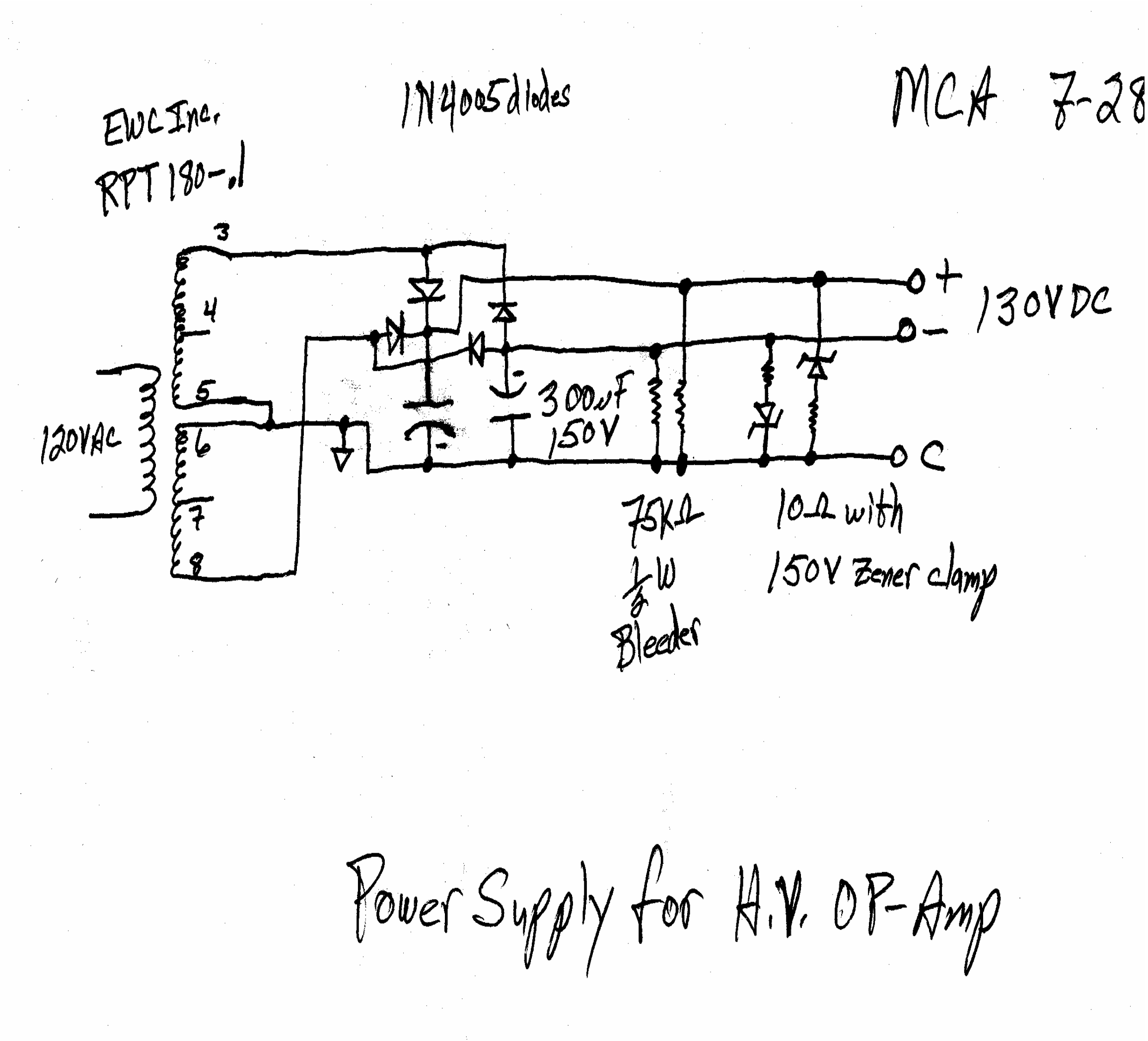
National Instruments: http://www.ni.com

ACKNOWLEDGMENTS

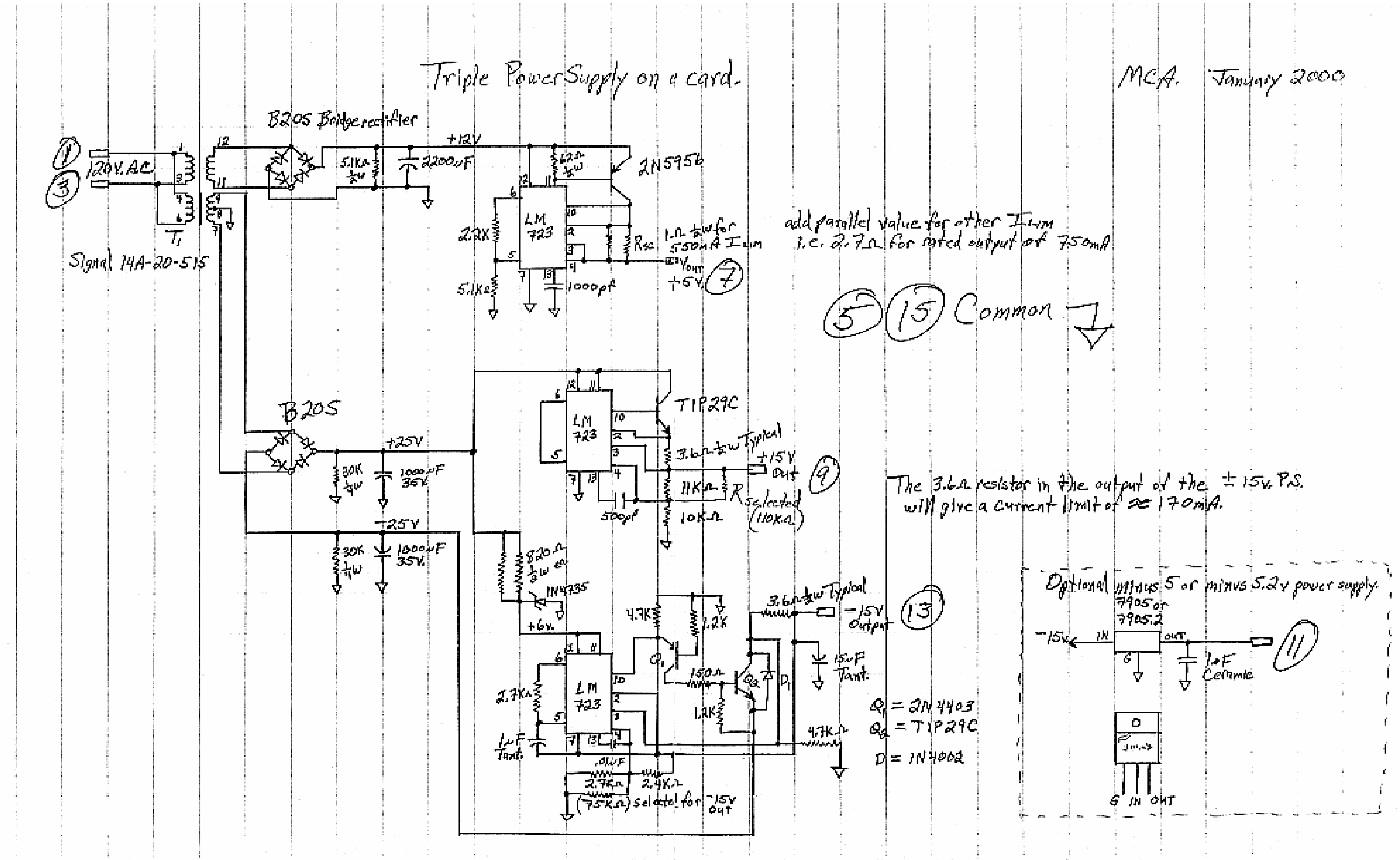
First, I wish to thank Dianne Engram, Elliott McCrory, Dr. Davenport and the other members of the SIST committee for this invaluable summer experience. Thanks to my supervisor, the talented Dr. Arden Warner, who has been a wonderful role model. Thanks to the entire Electron Cooling group for their help during this summer. Also, much thanks to the RF group, particularly Rene Padilla and Jeneen Irvin, for their assistance with the instrumentation amplifier.

APPENDICES

Schematic 1: ± 100 V power supply



Schematic 2: ± 15v + 5 V power supply



Schematic 3: Operational Amplifier circuit and Transimpedance amplifier

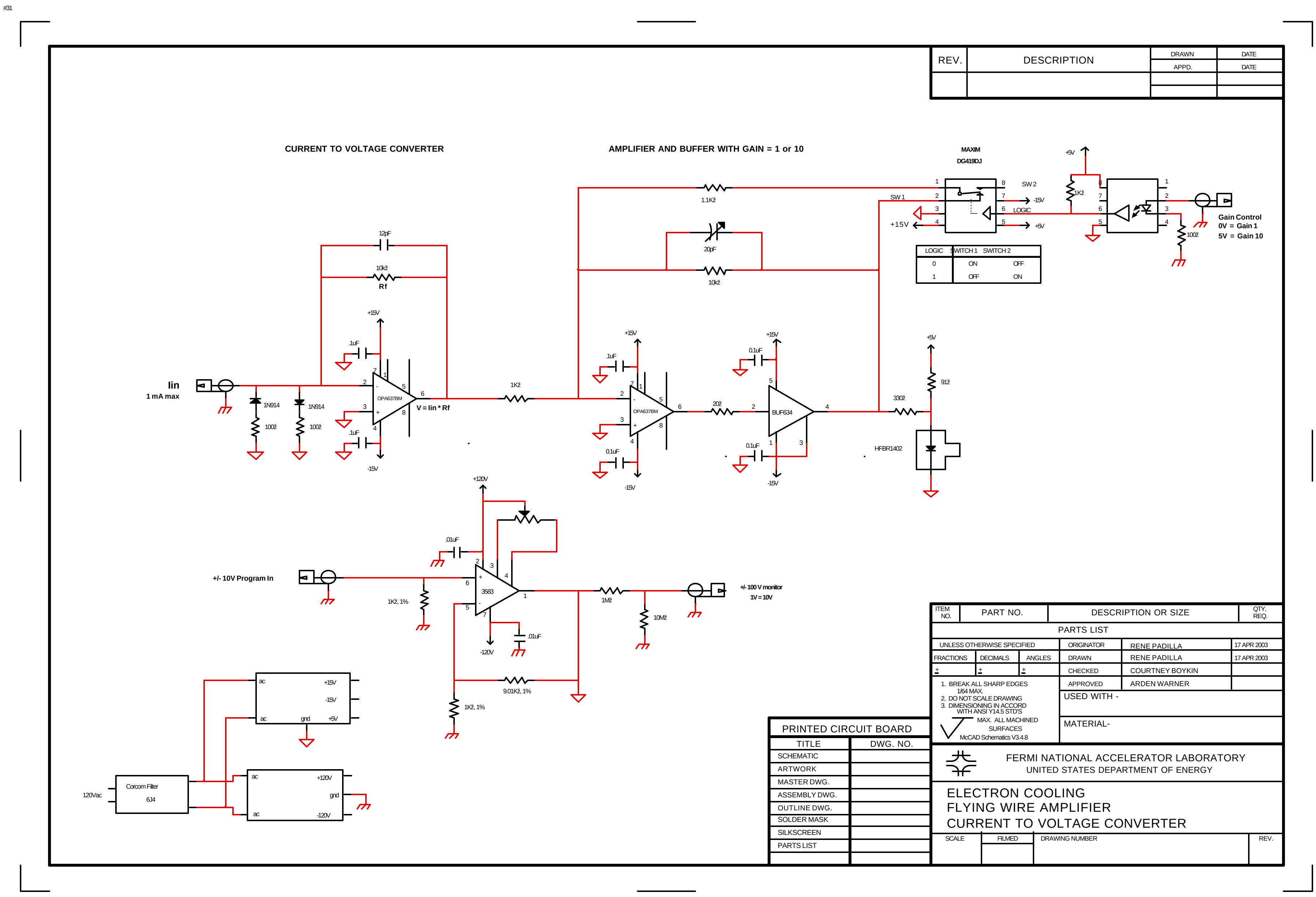


Diagram 1: Front Panel

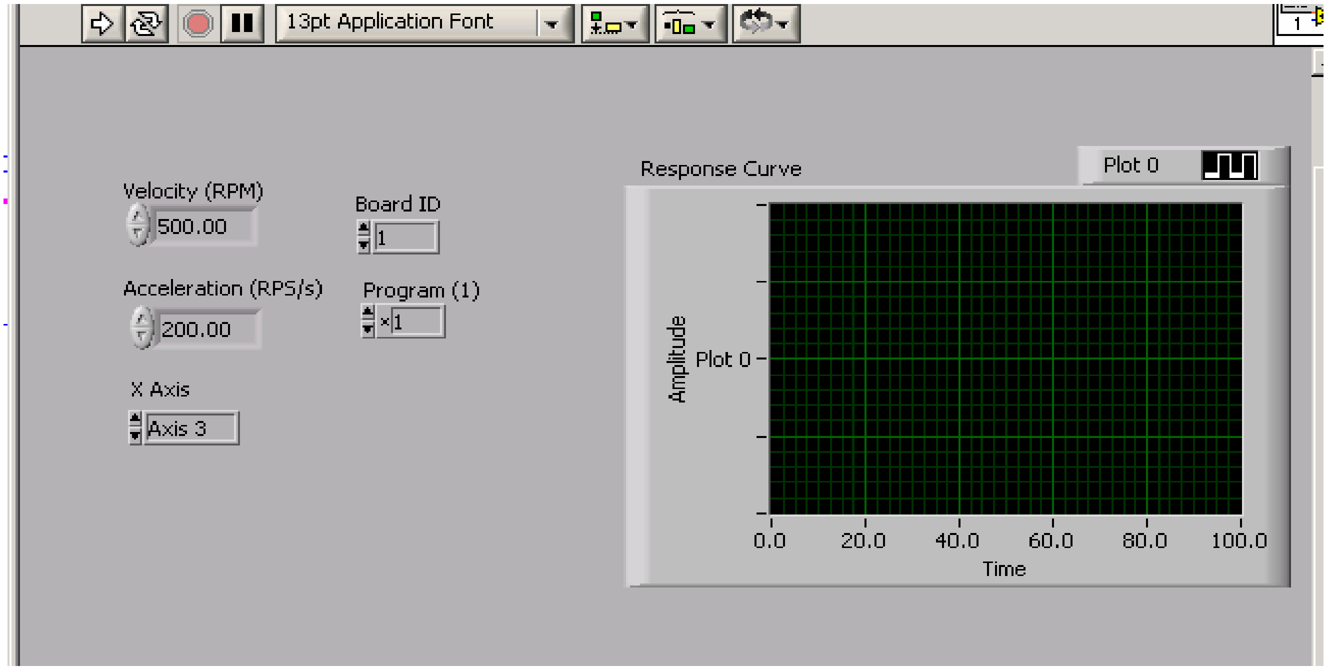


Diagram 2: Beginning of Block Diagram