Fermi National Accelerator Laboratory
Accelerator Division
Mail Stop 307
P.O. Box 500
Batavia, Illinois • 60510

Lifetime Measurements of Carbon and Diamond Stripping Foils Tested in the Fermi National Accelerator Laboratory Linac

Trivia Penns Frazier

Physics/Pre-Engineering Department
Dillard University
2601 Gentilly Blvd.
New Orleans, LA 70127

Supervisor: Doug Moehs
Accelerator Division
Fermi National Accelerator Laboratory
Batavia, IL 60510

Abstract

A foil testing apparatus was fabricated to test carbon versus diamond stripper foil life expectancy. The goal of this experiment is to find a target material more suitable for the proposed multi-mega-watt 8-GeV proton driver and booster system, which uses multiturn charge-exchange injection. Preparation includes tuning bending and quadrupole magnets and doing calculations of pertinent theoretical values, such as instantaneous current density and average power. The foil beam currents are carefully monitored using toroids and a data acquisition system. Results are then analyzed and compared to theory and presented using a series of charts and graphs. This paper reports the process, key factors, and maximum needed beam parameter when testing carbon and diamond foils in the Fermi National Accelerator Laboratory Linac 750-keV H^- beam line. Future goals are presented as well.

Introduction

In 1971, a proton linear accelerator, the Linac, was built at Fermilab. It operated at 201.25 MHz providing beam to the Booster at 200 MeV [9]. In March 1978, the Linac beam operated with H^- ions and the Booster began using H^- multiturn charge-exchange injection (CEI), which became the normal injection method for high-energy physics operation. In 1993, the high-energy portion of the original Linac was replaced with a more modern structure, increasing the Linac output energy to 401 MeV, using a side-coupled cavity linac operating at 805 MHz. Today it operates at ~15 Hz and includes a 20 keV H^- ion source, and a 750 keV electrostatic accelerating column.

Budker and Dimov discussed this concept in a paper in 1963 [14]. It is based on the capture of protons by stripping electrons from H^0 atoms or H^- ions on the closed orbit of a cyclic accelerator, and occurs when fast moving ions traverse a charge stripper, or foil. Charge strippers are essential devices in a heavy-ion accelerator complex because they increase the variety of acceleration schemes and the efficiency of injection. However, foils often limit the continuous operation of the accelerators because they break frequently so it is important to carefully select the material used [11]. Carbon foils, because of their commercial availability, expected lifetime, low multiple scattering, and relatively low cost, are used as targets for the 401-MeV Booster injection scheme to strip two electrons from the H^- ions of the beam [12].

Parts of Fermilab's existing Linac/Booster complex are nearly 35 years old. Maintenance and reliability are becoming a serious issue with these machines. Future new long baseline neutrino experiments will require factors of 5-10 increase in proton intensity. It is clear that such experiments at Fermilab are only feasible if a major proton source upgrade is undertaken [6]. The proposed Proton Driver has an 8-GeV output beam energy, a 90-turn injection scheme, and a 1-ms pulse at 2.5 Hz. In order to achieve multiturn injection at these intensities, a reliable target material is needed. Diamond foils with polycrystalline structure contain many of the superb physical properties of natural diamond that are thought to be suitable. Brookhaven National Laboratory (BNL) data, simulating the Spallation Neutron Source (SNS) beam on target conditions, presented at the Particle Accelerator Conference (PAC) 2001, indicate that diamond foils are superior to conventional evaporated carbon foils, exhibiting a lifetime approximately five-fold longer [2]. The lifetime of stripping foils depends on the melting temperature of the foils, the repetition rate of the beam, and the fabrication method of the foils. The performance of foils fabricated by various methods, under various beam conditions, has been reported in references [1, 2, 7, 8, 9]. The stopping power of a 300-ug/cm^2 carbon foil is 83.0 keV, for a proton beam at 750 keV. The peak energy deposition has been calculated to be 3621 +- 128 J/g for the 90-turn injection scheme at 8 GeV, with a calculated instantaneous temperature rise of 1991+-70 K, which is dangerously close to the melting point of carbon [15]. The maximum temperature of carbon foils is reported to be 2084 K [5]. The optimum goal of the experiment described here is to test the lifetime of diamond foils while achieving the same level of energy deposition, under conditions matching the 8-GeV injection scheme. The calculations further show that this can be achieved using 8.5 mA at 750 keV for 100 us [15]. This experiment is similar to the BNL diamond foil lifetime measurement, but it utilizes the 750-keV beam and transport system at Fermilab.

Experimental Setup

The experimental setup includes a vacuum chamber, an upstream H^- bending magnet and toroid, two collimators made of graphite, each having a 3-mm diameter aperture, a 300-350 $\mu g/cm^2$ carbon or diamond foil, a downstream toroid, and a data acquisition system. Figure 1, on the next page, shows a diagram of the testing station, including the positions of toroid 6 (T6) and toroid 7 (T7), and the location of the testing apparatus at W1.

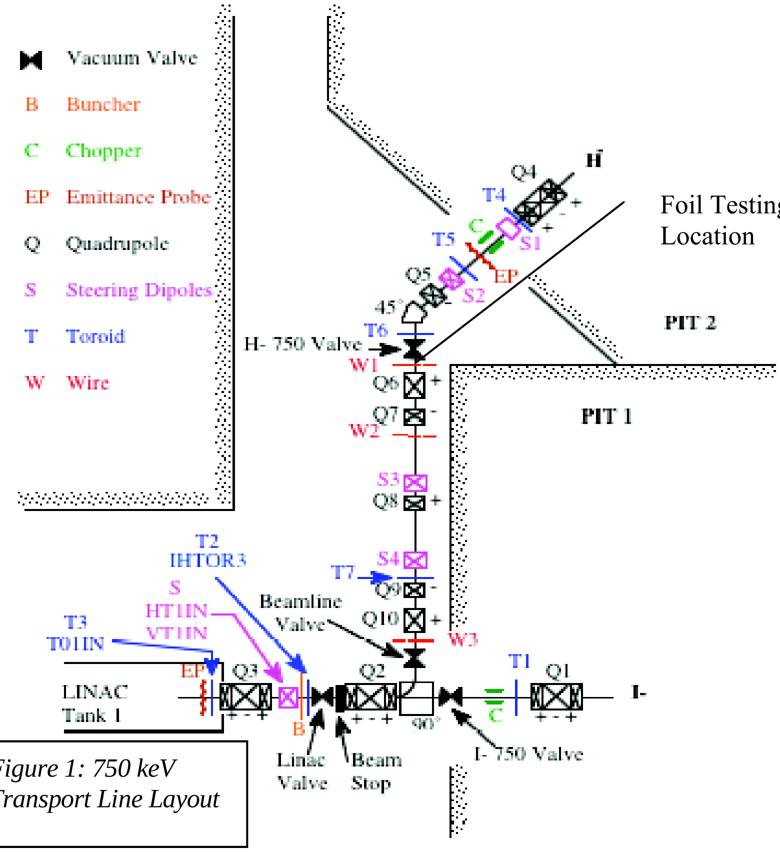


Figure 1: 750 keV Transport Line Layout

Figure 2 is a drawing of the diamond and carbon foil testing apparatus, drawn in Auto-CAD, and Figure 3 is a picture of the apparatus before mounting the foils. The diamond or carbon foil is mounted behind one of the graphite apertures, relative to the beam direction, and can swivel 90˚ in and out of the beam by a rotational vacuum feed through. The other aperture is used for tuning up the beam.

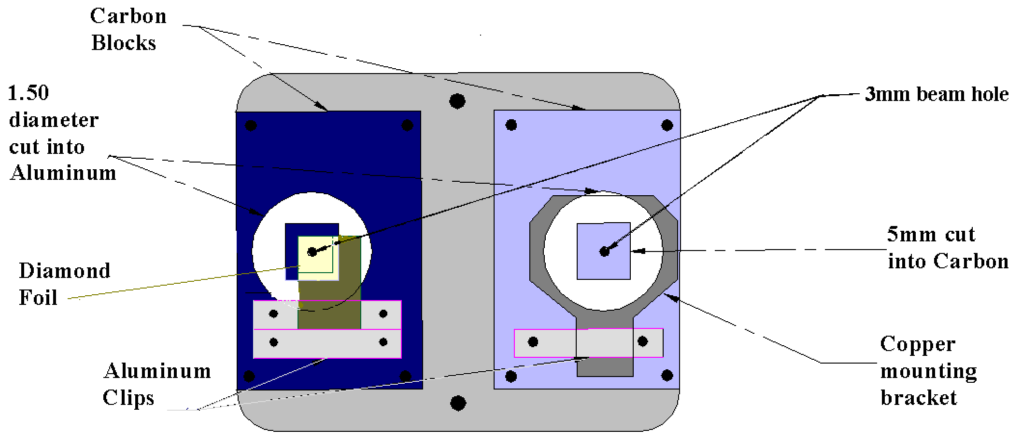


Figure 2. Assembly Drawing of Diamond and Carbon Foil Testing Apparatus

The foils are held in place by aluminum clips to prevent damage and keep them stationary. Before placing the foil in the beam, the bending and quadrupole magnets are tuned to get the maximum beam through the aperture. Quad magnet 4C (the center quadrupole magnet of a triplet at the beginning of the line) is tuned to reduce the beam intensity to 8.5 mA. The collimator is located ~5 mm away from the foil and controls the beam size on the foil.

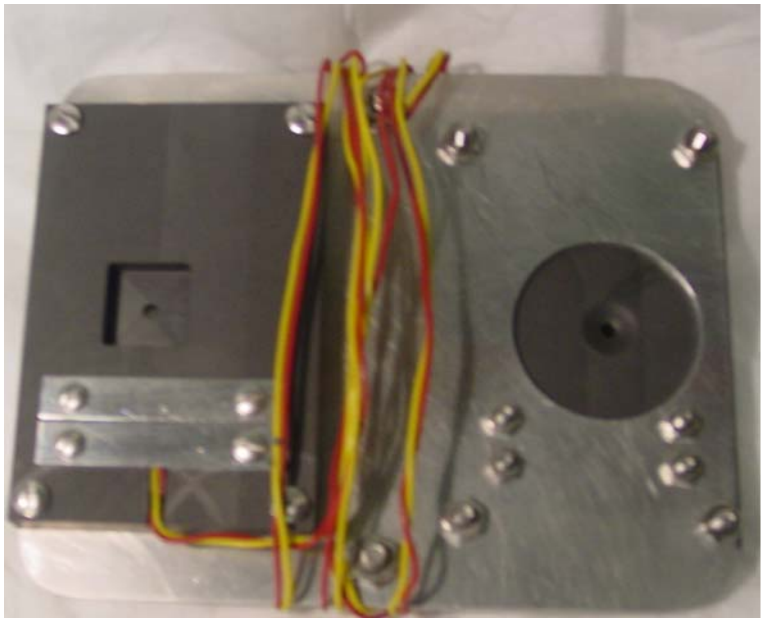


Figure 3. Picture of assembled apparatus

Toroid 6 is used to monitor the stability and amplitude of the current before the foil and toroid 7 is used to measure the current after the foil. Due to stripping, the beam current before and after the foil has opposite polarity. When toroid 7's initial value is reduced by 10%, the foil is considered broken. Data acquisition system D44, a data-logging page accessed by Fermi employees, is used to record the currents from T6 and T7, at an interval of 2 minutes.

Theory

The instantaneous current density of the H^- beam, and power going through the collimator hole with a Linac duty factor of 0.135%, can be calculated based on the beam current measured at T7, 8.5 mA. A uniform current density is assumed when dividing the beam current by the area of the beam hole, which has a 3-mm circular diameter defined by the collimator. Using the formula for the area of a circle, πr^2, the measured current density given in equation #1 is:

$$\rho = I/A = 8.5 \text{ mA} / 7.1 \text{ mm}^2 = 1.2 \text{ mA/mm}^2 \qquad \#1$$

where I represents the current in milliamps, A represents the area in millimeters squared, and ρ represents the average current density in the appropriate units. The true density at this location is unknown and is affected by the quadrupole focusing.

From there, the assumed instantaneous power going through the beam hole can be found by using equation #2:

$$P = V*I \qquad \#2$$

where P represents the instantaneous power in watts, I represents the current, and V is volts. We are using the 750-keV line, thus:

$$P = (750{,}000V)\ (0.0085A) = 6{,}375W$$

After including the duty factor, we get a sense of the maximum average power expected to go through the collimator:

$$(P)\ (D.F) = 6{,}375W*\ 0.00135 = 8.29\ W$$

Foil Preparation

Depending on the humidity of the surroundings, the foils tend to stick to things electrostatically, which can lead to damage at the edge where the foil meets the silicon support. The slightest whiff of air can also cause damage. Due to this frailty, certain precautions are necessary. The diamond and carbon foils must not be touched, but picked up with tweezers on their support frames.

The diamond foils are prepared at BNL before being shipped to Fermilab. The carbon foils must be mounted on a support frame before testing. This procedure consists of:

- Preparing a metal (either copper or stainless steel) frame holder.
- Putting small droplets of alphacyanocrylate ester (super glue) approximately ½'' from the center where the foil will be placed, and smearing the glue with a q-tip. See Figure A.

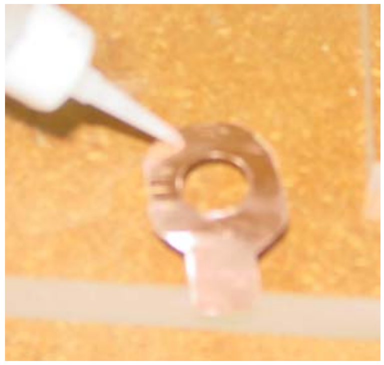


Figure A.

- Carefully placing the foil over the support frame so that the hole is covered, and allowing to dry. See Figure B.

- Using a blade to cut around the edges, labeling and mounting in stationary, covered setting until use. See Figure C.

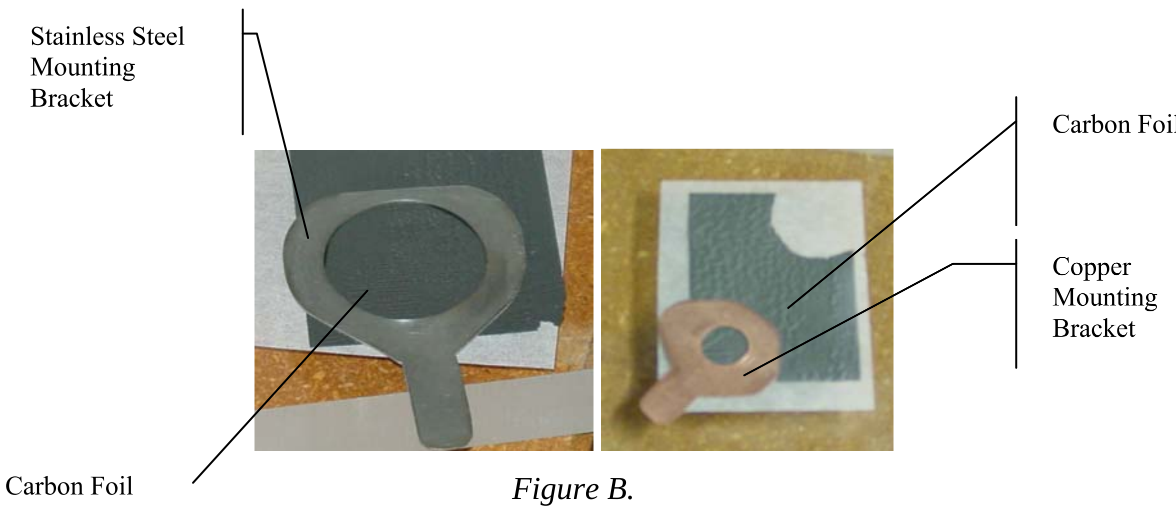


Figure B.

Figure C.

During the process of putting the foils in the beam, cracks may occur, which affects the lifetime. Curling also occurs due to stress, both intrinsic and thermal (stress produced by the large thermal expansion mismatch between the diamond and silicon growth substrate) [2]. The rotational feed through must be turned slowly to avoid damaging the foils.

Results

A total of 7 experiments were conducted over a 10-week period, which include testing 4 carbon foils and 3 diamond foils. A summary of the carbon and diamond lifetimes is shown in Table 1. The results are in the order that the experimentation was conducted and all current values are given in terms of peak beam current.

Table 1. Summary of Results

Foil Tested	Beam Repetition Rate (Hz)	Foil Density (ug/cm^2)	T6 Beam Current (mA)	Collimator Current with no Foil (mA)	T7 Beam Current with Foil (mA)	Lifetime (hrs.)
Carbon, #1	3.75	297	48	26	6	0.7
Carbon, #2	3.75	300	48	26.5	8.2	0.03
Carbon, #3	3.75	314	33	26.5	8.2	1.5
Carbon, #4	3.75	300	33	8.2	5.3	0.5
Diamond, #5	3.75	365	33	8.2	4	0.75
Diamond, #6	3.75	350	38	2	1	48
Diamond, #7	1.825	350	40	8.53	2	<2

Although the diamond foils do not exhibit lifetimes over 400 hours, they do exhibit a lifetime longer than the carbon foils; however, this lifetime was only achieved at a peak beam current of 1mA, not the desired 8mA. One data set of toroid outputs from experiment #3 is presented in Appendix A.

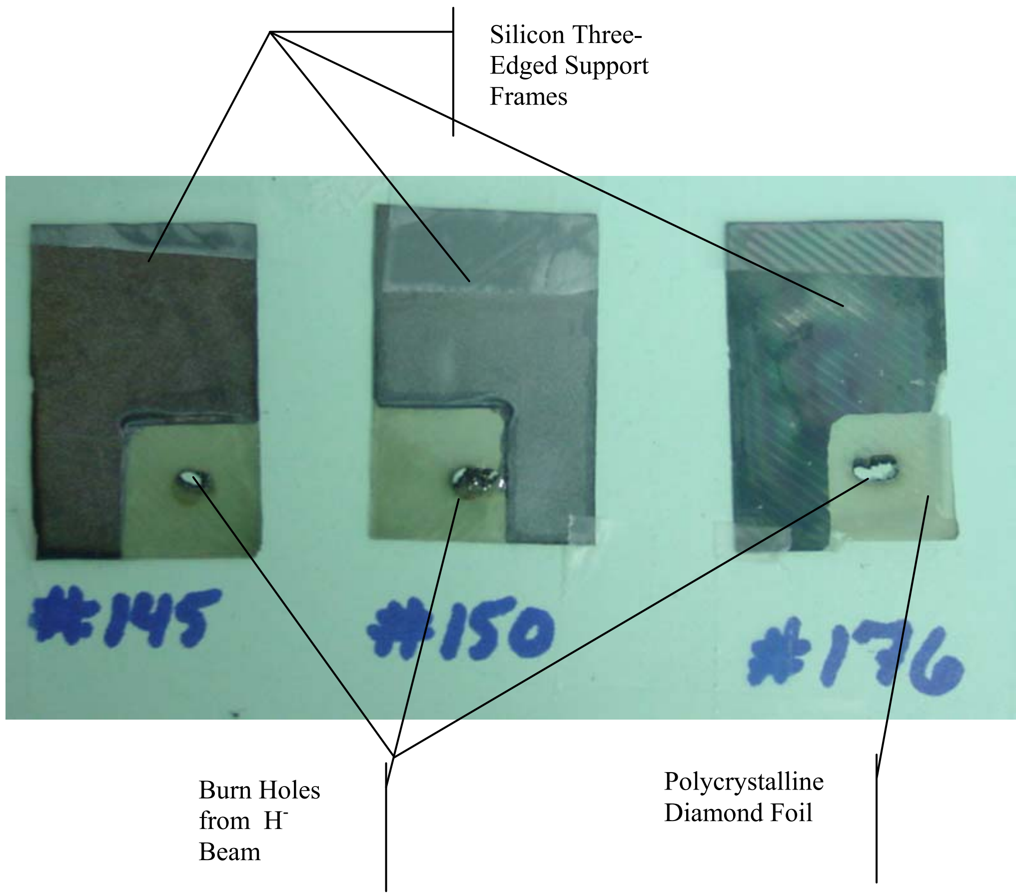


Figure D. Diamond Foils after Testing

Discussion

One possible systematic error has to do with the apparatus' symmetry. If the foil testing apparatus is asymmetrically designed, the 3 mm beam holes are not properly aligned with the beam and either the measured peak value would have an offset, or the toroids and quad magnets would have to be tuned for every experiment. To test for symmetry, the apparatus is placed in the beam without a mounted foil. The peak beam current values are shown, in Table

2. The first row of values is the result after tuning the toroids. The second row is after tuning the toroids and lowering the extraction voltage (the amount of voltage coming from the ion source). The numbers show that the apparatus is sufficiently symmetric and asymmetry does not affect the beam peak current through the foil.

Table 2. Symmetry Test

	Beam Hole Peak Current (mA)	Foil Location Peak Current (mA)
Before Lowering Voltage	~9	~9.5
After Lowering Voltage	~4.5	~3

The results as they relate to the theoretical values are given in Tables 3. The chart contains the current density, instantaneous power, and average power, along with the foil lifetimes. The duty factor is the beam repetition rate multiplied by the width of the beam pulse, 90 us.

Table 3. Calculations

Foil Tested	Uniform Current Density (mA/mm^2) = I / A	Instantaneous Power (W) = V * I	Average Power (W)	Lifetime (hrs.)	Duty Factor
Carbon	0.85	4,500	1.5	0.7	0.034%
Carbon	1.2	6,150	2.1	0.03	0.034%
Carbon	1.2	6,150	2.1	1.5	0.034%
Carbon	0.75	3,750	1.3	0.5	0.034%
Diamond	0.56	3,000	1.0	0.75	0.034%
Diamond	0.14	750	0.3	48	0.034%
Diamond	1.2	6,398	1.0	2	0.017%

Conclusion

The lifetime of the diamond charge-stripper foils was tested in the Fermilab Linac, using the 750-keV H^- beam, with repetition rates of 3.75 and 1.825 Hz and the desired peak beam current of 8.5 mA. The conclusions are as follows:

1. The optics of the 750 keV line do not work well on H+ beams.
2. Poor initial focusing may cause the beam to enter the collimator hole at an angle. Different techniques may be used to monitor the foils, which include placing a collector in the form of another toroid or Faraday cup directly behind the target to measure the beam current more accurately, and placing a window in front of or behind the experimental vacuum chamber to allow observation of the position of the beam.
3. The proton driver pulse length is 1ms.The relatively short 90us Linac pulse length may also have an affect on the foil lifetimes.
4. In the future, more testing and research needs to be done on the foils. All preferably repeated at 2.5 Hz to match the designed Proton Driver repetition rate.

With further testing, an assessment can then be made as to whether or not the foils are suitable for the Proton Driver upgrade. Based on present tests 4 and 5, there is no advantage to using diamond foils.

Acknowledgements

The author recognizes the advice, plenteous patience, and input of Douglas Moehs, Chuck Schmidt, Ray Hren, Jim Wendt, Jim Lackey, Weiren Chow, Mikhail Kostin, Milorad Popovic, Bob Shaw, Larry Allen, Bob Florian, Jim Wilson and the technicians at the shop; also, Elliott McCrory, Dianne Engram, and the entire SIST committee, for granting this enlightening, challenging, and most delightful opportunity at Fermilab.

References

[1] R.W. Shaw, V.A. Davis, R.N. Potter, L.L. Wilson, C.S. Feigerle, M.E. Peretich, C.J. Liaw, “Corrugated Thin Diamond Foils for SNS H- Injection Stripping”.

[2] R.W. Shaw, A.D. Herr, C.S. Feigerle, R.I. Cutler, C.J. Liaw, and Y.Y.Lee, “Thin Diamond Films for SNS H- Injection Stripping”, PAC 2003, Portland, OR, p. 617.

[3] C.J. Liaw, Y.Y. Lee, and Tuozzolo, “Lifetime of Carbon Stripping Foils for the Spallation Neutron Source”, PAC 2001, Chicago, IL, p. 1538.

[4] J. Farrington, D. Moehs, “H- ion beam characterization”, SIST 2002, Batavia, IL.

[5] C.J. Liaw, Y.Y. Lee, J. Alessi, J. Tuozzolo, “BNL/SNS Technical Note”, 1998, Upton, N.Y., no. 45.

[6] R.D. Hephart, “Plans for a Proton Driver at Fermilab”, Batavia, IL.

[7] J. Donahue, et al., “Measurement of H0 Excited States Produced by Foil Stripping of 800-MeV H- Ions’’, PAC 1993, Los Alamos, NM, pp. 369- 371.

[8] C. Hojvat, et al, “The Multiturn Charge Exchange Injection System for the Fermilab Booster Accelerator”, 1978, Batavia, IL, pp. 1-3.

[9] R. Hudson, R. Macek, “First-Turn Losses in the LAMPF Proton Storage Ring (PSR)”, PAC 1993, Los Alamos, NM, pp. 363-365.

[10] Mikhail Kostin, “MARS Simulations of the Stripping Foil Area”, H- mini-workshop 2004, FNAL Batavia, IL.

[11] H. Ryuto*, et al, “Preparation of Charge Strippers for the RIKEN RI-Beam factory”, 2004, Jpn, J. App. Phy. 43, p. 7753.

[12] R. C. Webber, C. hojvat*, “Measurement of the Electron Loss Cross Sections for Negative Hydrogen Ions on Carbon at 200 MeV”, FNAL Batavia, IL, pp. 1-2.

[13] J. Lackey, “Proton Driver Stripping Foils”, FNAL 2005, Batavia, IL.

[14] G.I. Budker and G.I. Dimov, “On the Charge Exchange Injection of Protons into Ring Accelerators”, International Conference 1963, CONF-114, pp. 1372-1377.

[15] Personal communication with Mikhail Kostin, Weiren Chow, and Douglas Moehs, supervisor.

Appendix A: Data from experiment #3 taken fromD44

Time	Toroid 6 (mA)	Toroid 7 (mA)
8:55:51	33.96912003	-1.477050781
9:09:51	33.9202919	-1.18408215
9:49:51	33.43201065	-1.086425781
10:07:51	33.43201065	-1.281738281
10:17:51	33.48083878	-1.135253906
10:19:51	33.62732315	-1.037597775
10:21:51	33.87145996	-0.598144531
10:23:51	34.11560059	-0.988769531
10:25:51	34.01794434	-0.891113281
10:27:51	33.9202919	-0.793457031
10:35:51	33.82263184	-0.695800781
10:37:51	34.06677246	-0.842285216
10:39:51	33.77380371	-0.695800781
10:59:51	33.9202919	-0.598144531
11:01:51	33.9202919	-0.500488281
11:19:51	33.7249794	-0.354003906
11:21:52	33.16443253	-0.354003906

The figures below are from the oscilloscope screen. Figure A1 is the current measurement before the foil is placed in the beam. Figure A2 shows the opposite polarity after. The current goes from ~33mA to ~-8.2mA.

Figure A1.

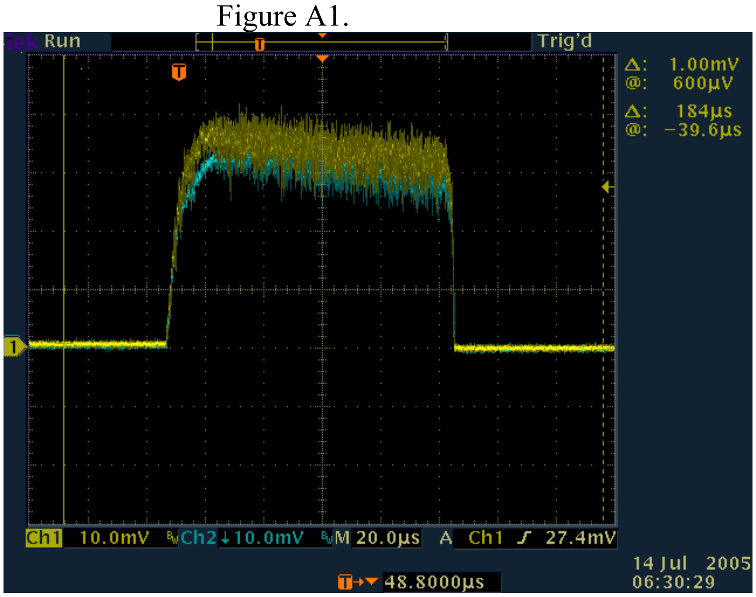
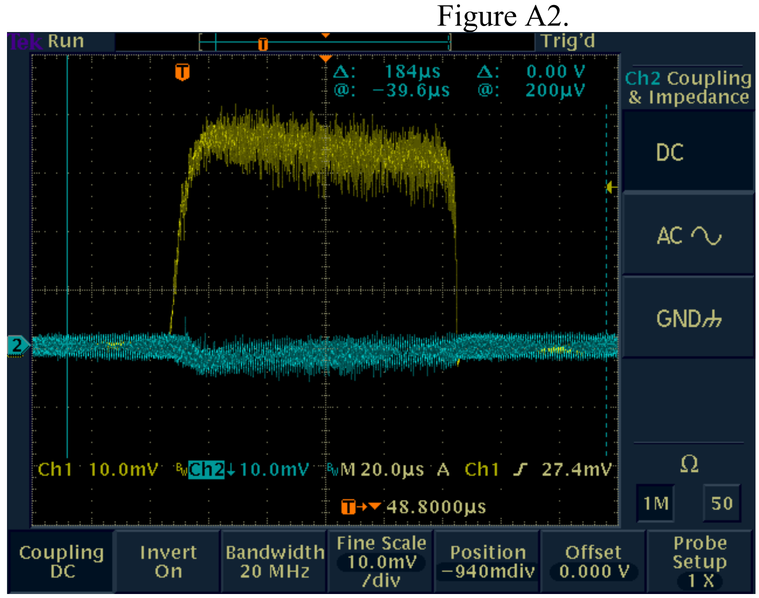


Figure A2.



Appendix B: The importance of a thermocouple connection

A number of factors influence precision of measurement throughout the experiment. Assurance must be made of a good thermocouple connection to receive the correct voltage and temperature measurements. We tested to see if the voltage would be accurately measured using a voltage multimeter, a thermometer, and a heat blower. The first series of tests are just with a thermocouple wire connected to a thermometer. One measurement is taken at room temperature, ~28˚C, the other at ~400˚C. The second series of tests are done with a type K thermocouple junction (chromel-allumel alloys), and the voltmeter is connected to an analog AC/DC converter. The results show values that are very close, as long as there is a reference point:

Table 1: Room Temperature Readings

Test 1-Room Temperature (volts)	Test 2-Room Temperature (volts)
0.183	0.325
0.184	0.193

Table 2: Hot Temp Readings

	Hot Temperature (Celsius)	Voltage (volts)
Test 1	401	5.1
Test 2	404	5.2

Our reference point is room temperature. In other cases, the reference point is a cool bath (0˚C), so we must take into account the difference of room temperatures when we begin the tests. As illustrated in Figure 5, both series, whether connected directly to a thermometer, or to a thermocouple then a voltmeter, display a voltage measurement of ~5V. This lets us know that making a type K junction will give an accurate reading when measuring voltage throughout the experiment. To create the thermocouple, on one end of a section of insulated wire a positive and negative charged tip is stripped and spot-welded together. A slit is created in the graphite blocks for the welded wires to be placed directly under the foil, and the other end of the wires are soldered to labeled leads in a junction. The labeled leads on the other side of the junction are connected to the AC/DC converter. Banana leads are then plugged into a voltmeter. From this junction, we are able to catch a sudden change in temperature throughout the experiment and record that data.