Characterization of the IOTA Proton Source

Lee Teng Internship Program Summer 2017

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Abstract

This project focuses on characterizing the IOTA proton source through changing the parameters of four various components of the Low Energy Beam Transport (LEBT). Because of an inefficient filament, current was limited to 2 mA when 40 mA is ultimately desired. Through an investigation of the solenoids and trims of the LEBT, we sought more knowledge about the optimum settings for running the IOTA proton source.

1 Introduction

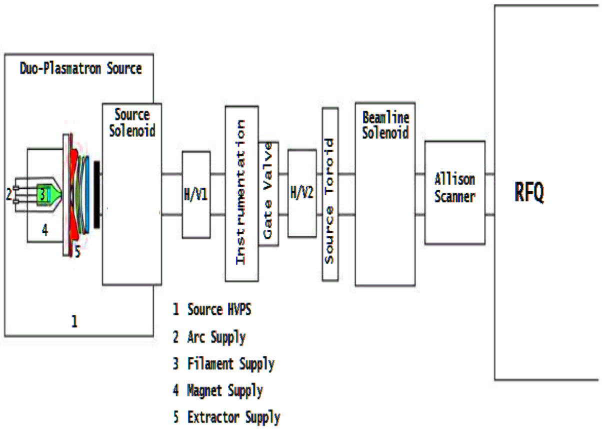
The Integral-Optics Test Accelerator (IOTA) proton injector emerged from the setups at the High Intensity Neutrino Source (HINS) facility at the Meson Detector Building (MDB) [1]. The HINS radio frequency quadrupole (RFQ) was performance limited, but the beam was sufficient for experiments. Once completed, the ion source will include the HINS ion source, a low energy beam transport (LEBT), a RFQ, and a buncher cavity. These will generate a 2.5 MeV proton beam for injection into the storage ring. This paper focuses on the ion source and the LEBT, not the full proton injector. Since the RFQ cavity is currently not in use, the beam is characterized to the Faraday cup located past the source magnet and the two beamline solenoids that aim to sculpt and direct the beam of ions. Once the beam is characterized, the components will be moved to the FAST enclosure at the New Muon Lab (NML) for full source commissioning. For more information on the specific components of the ion source, see section 2.

Protons and ions are drawn out to be injected into the RFQ through a change in potential that goes from negative to positive. It has been shown to be more efficient in energizing than going from a ground to ground state [5]. The priority was to parameterize the three solenoids and the source pressure. However, physical changes also occurred throughout the course of testing. The original filament, used to date, was installed as a part of the HINS project and has likely been exposed to atmosphere, severely limiting the source output. Efforts are underway to replace this, but the following data reflects the original filament. This is alright at this stage, as the goal was to successfully produce beam current and investigate operating parameters.

By the end of June 2017, beam current was formed and the power supply reached 20 kV, which will be the limit for a while due to safety concerns. The goal is to eventually bring the power supply to 30-40 kV. 2 mA of current was achieved, a significantly higher output than at the beginning of testing.

2 Equipment/Methodology

Figure 1: Low Energy Beam Transport (LEBT).



The Faraday cup is located in place of the RFQ depicted above in Figure 1. The Faraday cup leads the beam through a 10 kΩ resistor, allowing the oscilloscope to measure current. While connected to the ACNET network and available for added parameters, there is currently no current added to the toroid depicted in the middle. The LeCroy oscilloscope offers averaging techniques, allowing for a cleaner waveform. These tests used 10-20 pulses per averaged point.

Figure 2: Waveform at 2.0 mA. Blue trace represents beam current and the red trace represents current integral (Vs).

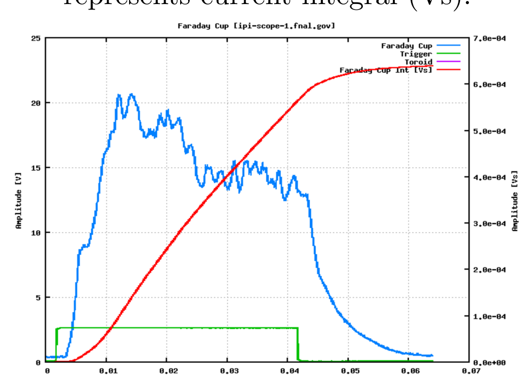
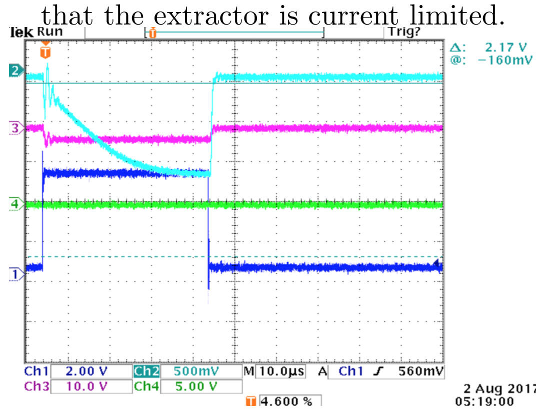
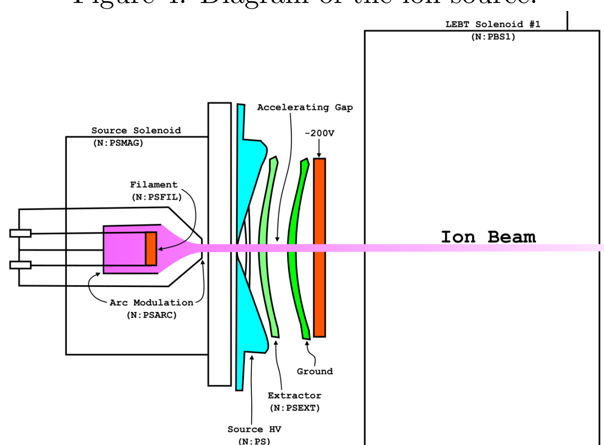


Figure 3: The source scope in the high voltage rack. Channel 1 is the arc current, channel 2 is the arc voltage, and channel 3 is the arc trigger. Any toroid output is below the chart threshold, which exists if beam current is formed. The downward-curved shape of the cyan trace shows that the extractor is current limited.



2.1 Duoplasmatron Source

Figure 4: Diagram of the ion source.



The ion source components are from the former HINS program, but new power supplies were required as well as configuration of the source connections in order to restore operation. This included copper bands that initially acted as terminals on the stages of the acceleration column. The bands initially used for connections along the accelerating column were found to be insufficient at 20 kV, so aluminum balls with set screws were fabricated to provide better contact and avoid arcing due to corona or loose connections. These additions were completed later in the study, and most likely alleviated some of the sparking experienced earlier. A duoplasmatron source is advantageous as it allows for a large beam intensity, high gas efficiency, and a capability to produce negative and multicharged ions

[7]. In the state of initial testing, the source functioned properly but lacked more rounded clamps and a newly coated filament. The main purpose of this construction was to see if current was feasible. This preliminary construction also allowed for prediction of future problems, as well as the ability to gauge roughly where limits are in regards to operation. The choice of 20 kV comes from consultation with ESHQ, so it is possible to increase the high voltage in the future, given that communication occurs.

The starting point was the observation from earlier studies that the three main factors for operation were the geometry of the source, the source pressure, and the cathode/anode discharge [7]. Since the geometry is fixed, this project focuses on varying the source pressure, beamline solenoids, and source solenoid. Inside the duoplasmatron, the cathode is depressed to -20 kV, forming a plasma that flows towards an open space right before the anode. Electrons are repelled at the negatively charged anode, while the ions flow through the small hole. In the free space the ion plasma begins to grow in size, until it reaches the source solenoid. With proper tuning, extraction is maximized, allowing for a strong beam current.

2.2 Filament Coating

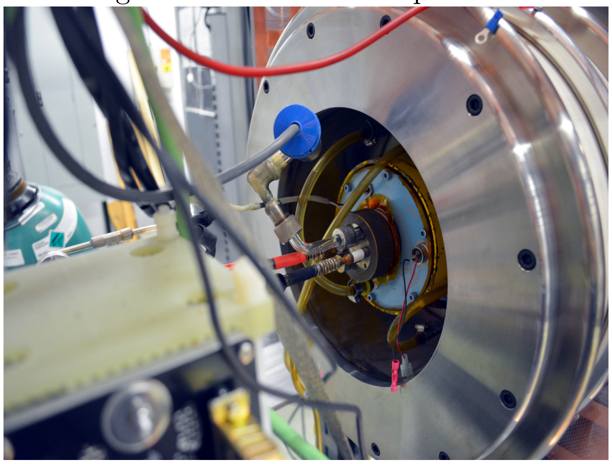
Figure 5: Coating a filament to test the procedure. This filament will temporarily replace the coated one.

The source filament uses a variety of chemicals to facilitate production of a plasma. Ions are drawn from this plasma, so a large production is desirable to produce a beam strong enough to measure in mA. When increasing the filament current, it is important to keep a check on the vacuum pressure, as increasing the current too quickly will ionize the gas around it and increase the vacuum pressure rapidly. As standard operations suggest 105 mTorr for vacuum pressure, it is suggested to increase filament current slowly so the PID can regulate the vacuum pressure below 125 mTorr. The cause for the vacuum change is the excess material being burned off of the filament, so that a clean beam can be created. When current runs through the filament, it heats up, priming the filament coating to ionize the hydrogen gas in the source. Because of the composition, compounds collect on the filament when it is not in use. This results in outgassing from the filament as these compounds vaporize with increasing current. During nominal operation a PID loop keeps the source pressure regulated to within 1 mTorr of a set point. Allowing the vacuum pressure to jump too high can cause damage to the duoplasmatron.

As seen in section 3, a poorly coated filament greatly affects proton production and beam current. The filament is constructed on a foundation of nickel mesh, which is then dipped into the coating mixture [6]. At the base of the mixture is $BaCO_3$ and $SrCO_3$, which combined is known as a "radio mixture". The whole coating will be referred to as Radio Mixture 3. The original mix then has to be added to a liquid hydrocarbon, which in this case is banana oil. This is paired with multiple other extra chemicals to create the final mixture. The filament must be dipped and dried in this mixture multiple times, as a single coating leaves unfilled cracks. As of now the coating is naturally dried, though it is possible to heat dry. Once a new filament is installed, significantly more beam current is expected and less of an arc current limit (currently 1.98 A) on the filament. It is expected to produce 40-60 mA of beam current and a full arc current of 25 A.

2.3 Source Solenoid

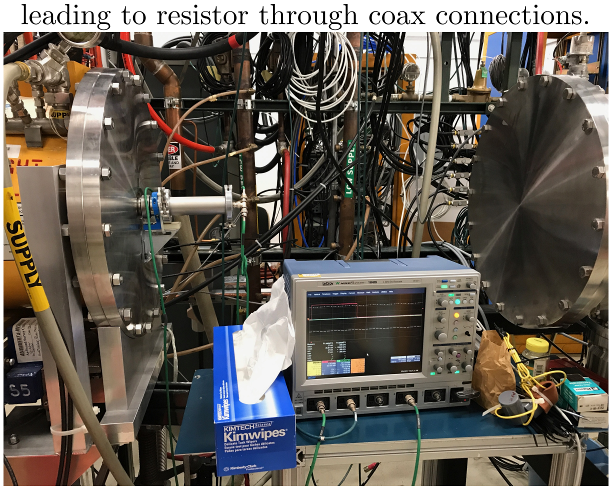
Figure 6: Solenoid with open box.



This is located after the filament, serving as a shaper for the ions that are pulled out. A low emittance is desired, so the magnetic field produced by this solenoid condenses and shapes the beam so that a "thin" beam passes through into the RF cavity. A low starting emittance is desirable, as the beam will naturally expand once it enters the RFQ.

2.4 Faraday Cup

Figure 7: Faraday cup (thin cylindrical tube) leading to resistor through coax connections.



The Faraday cup is the end of our experimental section, attached static at the end of the LEBT. It is made of OFHC copper, measuring 1" by 1.75" by 0.5". The signal is directed out of the UHV system by means of a 0.051" diameter stainless steel wire. The Faraday cup is attached remotely via a horizontal pneumatic actuator, and the data pulled from this helps form the plots and measurements found in the oscilloscope [2].

2.5 ACL

The Accelerator Controls Network (ACNET) facilitates operation of the proton source. Accelerator Control Language (ACL) code is written so that measurements can be taken automatically without having to record individual values. An example of a plot generated by hand can be found in section 3. Two separate codes were created to take traces and plots from the scope. The routines used are:

- Raster scan of the LEBT solenoids and heat map generation
- Continuous loops for faraday cup statistics
- Code to collect scope waveforms

Using these resources while changing source parameters allows the raw data to be saved as well as plotted so individual parameters could be graphed and measured in Excel appropriately.

2.6 Experimentation

The independent variables studied were source solenoid current, beamline solenoid current, and source pressure. One parameter is varied at a time while leaving the rest of the parameters at standard (see section 3). The peak of current is measured for this one parameter, which is considered the optimum setting. The optimum setting is applied for testing the next variable. The overall current peak for all optimum settings is the ideal conditions for operating the source. These conditions could change when the source is rebuilt and the filament is recoated.

3 Results

3.1 Initial Scans

The data found below reflects tests run during week five. These were recorded by hand to gain a level of comfort with operating the ion source. Currents were calculated from Ohm's law with a voltage output and a 10 kΩ resistor. Current originally only reached to singular µA, and was now seeing values around .20-.25 mA. Readings are estimated based on the range of oscillation, limiting accuracy.

Figure 8: Beam current as a result of changing horizontal trims. Beamline solenoids turned off.

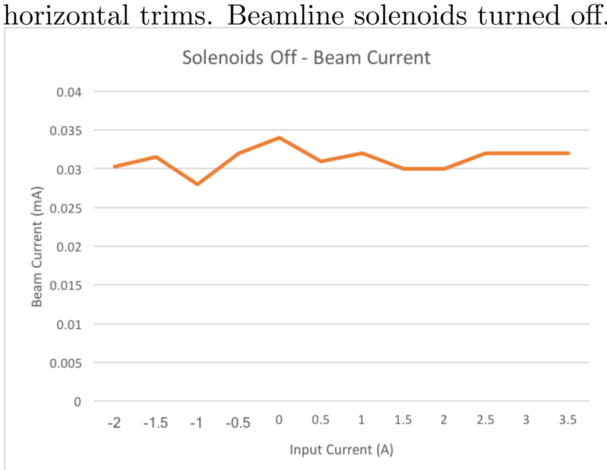


Figure 9: Changing horizontal trims. Beamline solenoids turned on.

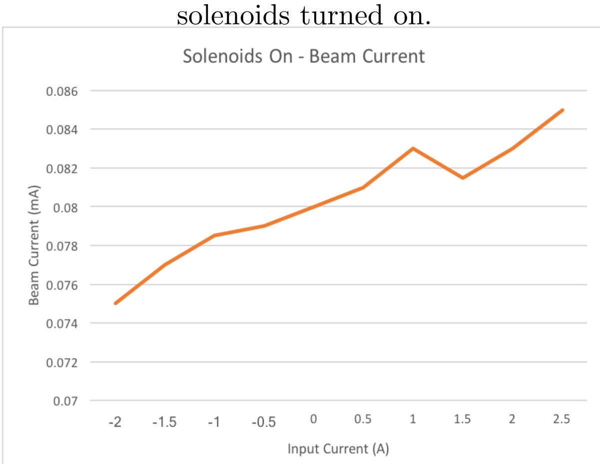
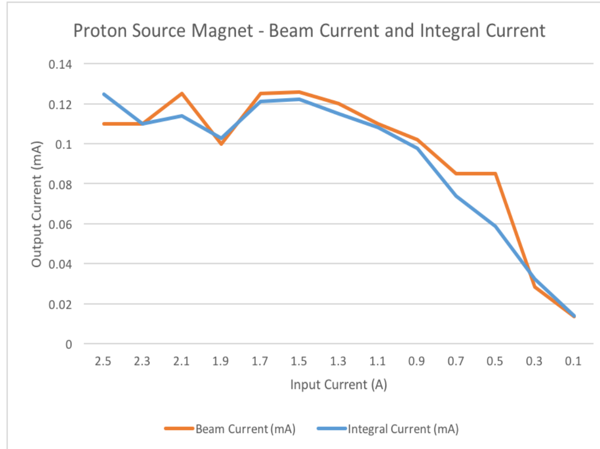
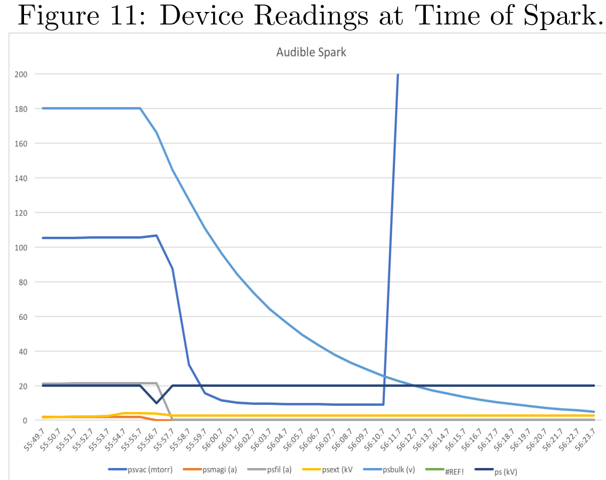


Figure 10: Changing source solenoid current.



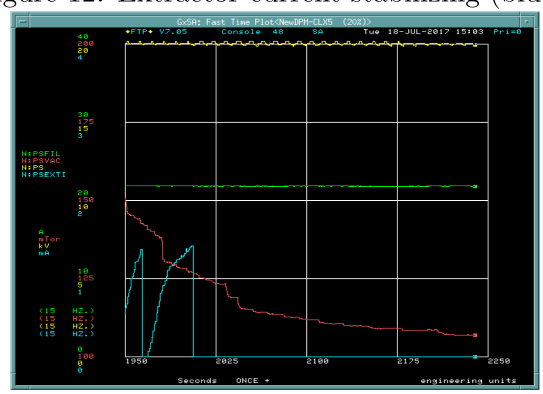
In week seven, the ion source was in the process of being rebooted after a "spark" (see figure 11). The spark caused all power sources to shut off, and a PLC card and arc modulator bulk supply had to be replaced as smoke could be smelled from the high voltage rack. Vacuum is seen to rise drastically due to the reboot of the VAT valve. Since the pressure is regulated, it began to decrease back to the 105 mTorr. There was a dip in the high voltage power supply. The source pressure tripped the filament supply, and one instance of smoke caused the detector to trip all other supplies.

Figure 11: Device Readings at Time of Spark.



Connections were changed to prevent current running through the valve, which probably contributed to the sparking. The aluminum balls were ready for installation, preventing future sparking. After alleviating these issues, a consistent beam was achieved with different extractor behavior. While extractor current interferes with the strength of the beam current, it can be accounted for through proper parameterization. At a less optimal setting, the extractor current is seen to vary over a large time frame. The goal was to alter the pressure to see if this variation can be eliminated. Vacuum pressure was varied by 10 mTorr while at 0.5A increments of the solenoid current. Source pressure is maintained by a leak valve to the H_2 bottle controlled through a PID controller. The change is not instantaneous so the resulting beam current should always be compared to the source pressure read back rather than the set point. Below are the conditions where the highest beam current was achieved.

Figure 12: Extractor current stabilizing (blue).

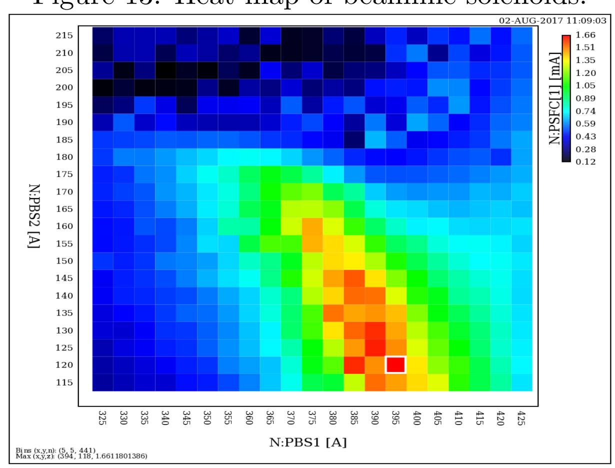


The extractor current, represented by the cyan line varies and then drops below the chart boundaries after optimizing. However, once the source reached 125 mTorr on the vacuum pressure, the beam disappeared and there was a dip in the voltage. There was a failure in operating the modulator bulk supply, and this prevented further vacuum testing that day. The concern was that continuing to use the old filament could cause permanent damage to the duoplasmatron. Replacing the current filament with a freshly coated one will allow for a cleaner beam and a controllable pulse that isn't emission limited. However, steps are being taken to redo some of the electrical connections, as it is possible that the high voltage is not being distributed properly.

3.2 Final Scans

These tests took place during week nine. A new modulator bulk supply had been added, and the source was more stable than during the previous scans. It was possible to leave the high voltage and filament current on so that the filament remained outgassed. A simple tuning with the source occurred where parameters were tuned without measurement, and this occurred with each device to see the highest current possible. The source reached .7 mA of beam current, compared to the .25 mA achieved in the first weeks of operation. Since the source was stable, datalogging techniques were applied to perform scans on single parameters. First, the beamline solenoids were investigated. Since the two solenoids work in tandem, a heat map was applied to find the optimal combination of solenoid currents. In the heat map, the highlighted square represents the highest beam current achieved, and the respective solenoid currents can be traced back via the plot axes.

Figure 13: Heat map of beamline solenoids.



The first solenoid was then set to 395 A and the second was set to 120 A. Current ran consistently between 1.5-1.6 mA. Leaving these parameters, the source solenoid was scanned through a time plot where values were linearly decreased, starting from 2.5 A. There was a peak observed at 2.45 A, in which beam current reached 1.96 mA. There were instances after the scan that the beam current reached over 2 mA at 2.45 A of source magnet current. However, leaving the source solenoid at 2.4 A is not suggested as water temperatures were reaching 40 C. Until heating capabilities are improved, the source should be run at less than 2 A. Source pressure was investigated, and while current increased as pressure increased, it is dangerous to increase the pressure, as apparent from the previous failure at 125 mTorr. Current reached approximately 2.0 mA during these tests.

Figure 14: Varying source solenoid currents (magnet current v. Faraday cup output).

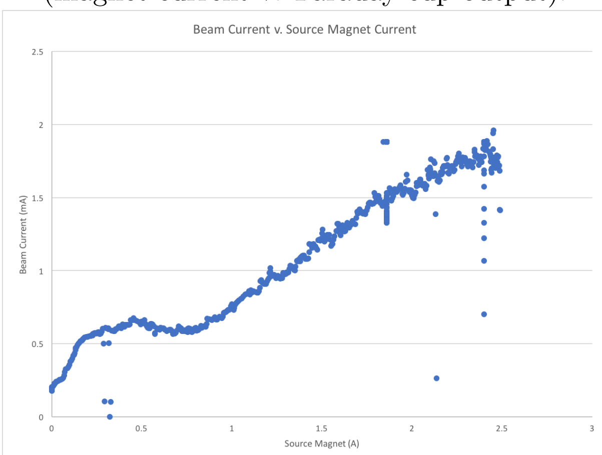
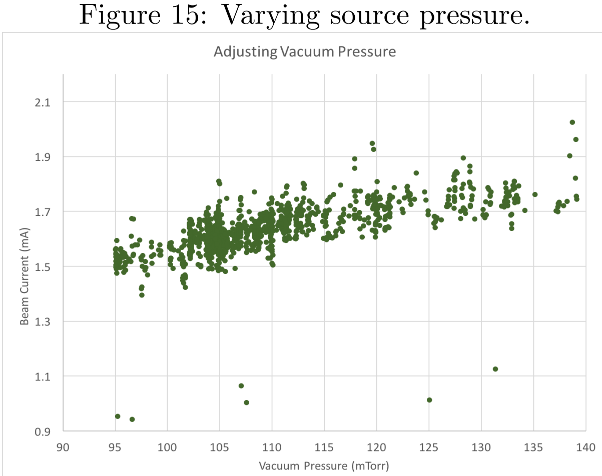


Figure 15: Varying source pressure.



Maximum beam currents were found for the following settings: source solenoid magnet current of 2.4 A (Fig. 14), source pressure of 138 mTorr (Fig. 15), and LEBT solenoids 1 and 2 settings of 395 A and 120 A respectively (Fig. 13). The solenoid magnet should not be run above 2 A to avoid damaging the source solenoid, and the steady increase of source pressure between 90 and 125 mTorr only resulted in a .2 mA improvement over the selected nominal of 105 mTorr. These conditions yielded a maximum 2 mA of beam current on the Faraday cup (Fig. 2).

4 Conclusions

There are future improvements planned for the IOTA source, as a replacement filament is being prepared for installation. The oscilloscope outputted 2.0 mA of current, and the new filament will meet the 40 mA requirement. The design for the source calls for 25 A of arc current, and the low achievable arc of 1.98 A limits the number of ions that can be injected. With a newly coated cathode, a full arc current of 25 A can be achieved. Using the 2.0 mA of beam, I was able to demonstrate that the output current is dependent on the independent variables of source pressure and solenoid current. A bending dipole magnet will be installed after the faraday cup to create a momentum study on the beam constituents.

5 Acknowledgements

I would like to thank my mentor, Kermit Carlson for showing me not only the workings of the IOTA source, but the activity going on throughout NML as a whole. I was able to get hands on experience in multiple areas to enrich my knowledge of the FAST division at Fermilab. Thank you for guiding me through the physics I needed to fully understand the process of injecting protons, and for your patience throughout the various problems encountered throughout the project. I would also like to thank Dean Edstrom for teaching me about ACNET controls and how to efficiently collect data using ACL code. I learned a lot about how accelerator controls work, and this allowed me to carry out experiments confidently and feel comfortable turning on and working with the ion source. Finally, I would like to thank my supervisor, Eric Prebys, for helping make my learning experience as a Lee

Teng intern the best it could be. I was also lucky that he is a major part of the IOTA program, so I was able to use him as resource when needed.

6 References

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