

Automating the Monitoring and Control of an Experimental Beam Line at Crocker Nuclear Laboratory

Berlin Del Aguila

August 19, 2019

Abstract

This document discusses the steps taken to automate the monitoring and control of an experimental beam line at Crocker Nuclear Laboratory (CNL). The processes required were to simulate, program, and calibrate the beam line as described below. Experimental results are also mentioned within the document.

1 Introduction

Similar to other particle accelerators, the isochronous cyclotron at CNL allows scientists and engineers to investigate the properties of particles at high energies. Table 1 characterizes each particle accelerated within the cyclotron with its corresponding energy. CNL provides services to national labs and private industries to study the effects of radiation on electronics deployed in spacecraft, along with performing ocular cancer therapy treatments. My project of automating the cyclotron’s beam line will facilitate future applications and measurements such as beam intensity and emittance.

| Particle Type | Energy(MeV) |
|---------------|-------------|
| Proton | 1 to 64 |
| Deuteron | 15 to 40 |
| Alpha | 5 to 80 |
| Helion | 6 to 75 |

Table 1: The particles accelerated at CNL and their respective energies(MeV).

2 Principle of Operation

Concepts from electricity and magnetism apply to particles in cyclotrons as they are accelerated outward from the center in a spiral path. The acceleration is achieved with a constant magnetic field and a high frequency, oscillating electric field.

Figure 2 shows the d-shaped electrodes known as “dees” in which the magnetic and electric fields are applied. Each bunch of particles that cross the gaps between the dees, are accelerated and kicked outward into a new orbit. Note that because the cyclotron is isochronous, the orbital period of each particle bunch remains the same. The set of dees are enclosed in a vacuum and are placed in between the north and south poles of a large magnet as shown in Figure ??.

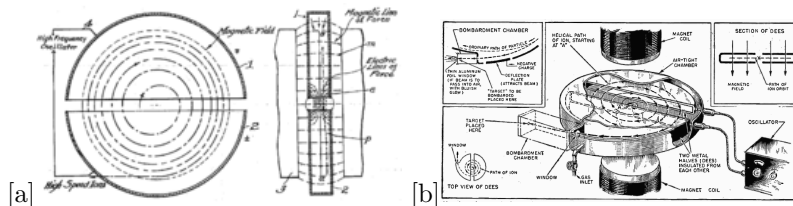


Figure 1: (a) Path taken by charged particles within two dees. (b) Two dees placed between the two poles of a large magnet. A Beam line for extraction is also illustrated.

As the particles reach the outer rim of the dees, they undergo a multi-step extraction into their designated beam line. Within the beam line, the particles experience a focusing effect within a set of quadrupole magnets also known as quads.

3 Beam Focusing

As mentioned in the previous section, the particle beam goes through a set of quads in which the beam gets bent, steered, and focused. A quadrupole magnet is a set of four magnets oriented to create a magnetic field whose magnitude is zero at the center and increases rapidly as it moves outward in the radial direction. Applying the magnetic force equation shown below, reveals a focusing effect on one axis of the quadrupole and a defocusing effect on the other axis. This becomes an issue when trying to focus the beam in both axes.

$$F_B = q\mathbf{v} \times \mathbf{B}$$

However, because quads act as lenses much as in optics, photo theory concepts have been used to achieve an overall focusing effect. The photo theory tells us that setting two opposite lenses back to back with some distance apart will lead to an overall focusing effect regardless of the order in which the lenses are placed. This concept is shown below in Figure ?? and Figure ?. Likewise, setting two quads back to back some distance apart, with an inverted polarity on one of the quads, provides an overall focusing of the beam. Once focused, the particle is then free to exit the beam line and hit its target.

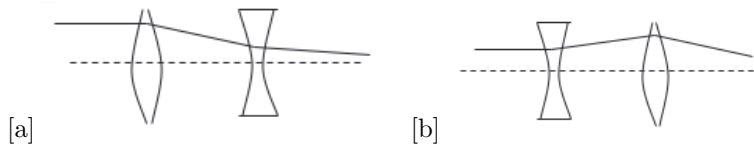


Figure 2: (a) Focusing from convex to concave lens. (b) Focusing from concave to convex lens.

4 My Project and First Simulation

This summer I applied the concepts I learned from accelerator physics and cyclotron dynamics to my project regarding the automation of an experimental beam line. Using Python, a Raspberry Pi, and LabVIEW control modules I controlled the current applied to a quadrupole magnet in an effort to focus the particle beam.

Figure 3 displays the equipment used in the first simulation to observe how a varying magnetic current bends a simulated beam up and down on the oscilloscope screen. In order to focus the beam, a python program was written

to vary the magnet's current in a way to re-position the beam at the center of the screen.

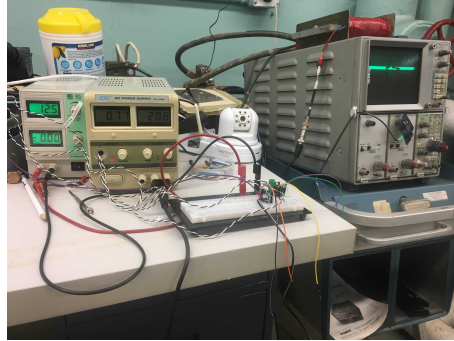


Figure 3: Equipment used in the first simulation.

Left to right: Two power supplies, electronic chips/components on breadboard, 5110 Tektronix oscilloscope, and above the oscilloscope is the magnet used to bend the beam.

The current supplied to this magnet was controlled with LabVIEW modules (not shown) and used to bend and re-position a simulated beam back to the center of the oscilloscope.

5 Code Algorithm

Two pieces of code were created after establishing a general idea of how to automate the beam line. The first code (on a PC) supplies the magnet with varying current values to be iterated over. For each iteration, the second code on a raspberry pi takes a photo of the particle beam on a phosphor screen. The image then undergoes image processing and the code measures the dimensions of the beam spot. The dimensions of the image are sent back to the first code after each iteration in which they are appended to a list. After all current values are iterated through, the first code sorts through all the dimensions in the list and finds the minimum dimension with its corresponding current value. This minimum dimension is of high interest because it's the instant when the beam is the most compressed and focused. The first code then uses the LabVIEW control modules to set the magnet's current value to the equivalent minimum dimension value, producing a focused beam.

6 Second Simulation and Experimental Set-up

To confirm these codes were sufficient to tune the quads and focus the particle beam, a few adjustments were made to the first simulation shown. Various sized beam spots were printed to provide dimensional variations to the

raspberry pi code as shown in Figure 4. Similar to the first simulation, a varying current was supplied to the magnet to be iterated over. This time, the code took a photo of the beam spot and measured its dimensions. I would then flip to the next printed beam spot, and the process would be repeated until all beam sizes had been iterated. Finally, the code would set the magnetic current back to the value of its corresponding minimum dimension.

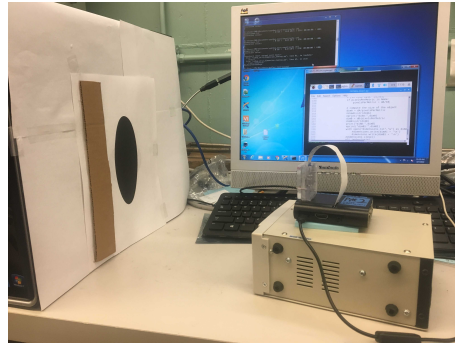


Figure 4: The altered simulation used to test the codes on the experimental beam line.

After verifying the simulation was functional, the experimental beam line was prepared to test the codes. A phosphor viewing screen was placed at the other end of the beam line with a raspberry pi camera sitting across from it to capture images of the beam. Adjustments were made to the image processing steps in the codes to accommodate the beam's characteristics. Additionally, a relationship between the input current supplied by the LabVIEW modules and the output current of the quads was recorded and plotted on an Excel to ensure the desired range of current values were not exceeded.

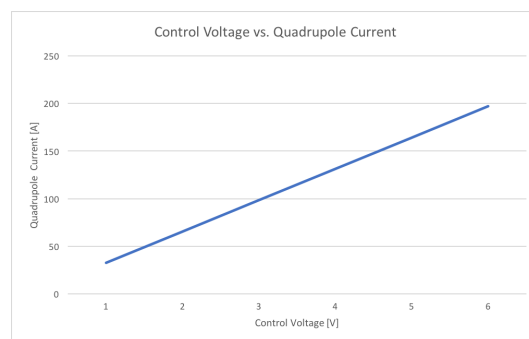


Figure 5: The plot above shows the linear relationship between the voltage supplied by the LabVIEW module to the quadrupole magnet's output current.

7 Results

The results gained from running the experiment showed the beam bending and focusing as the quads were tuned. A few of the beam spots from the experiment are shown in Figure 6.

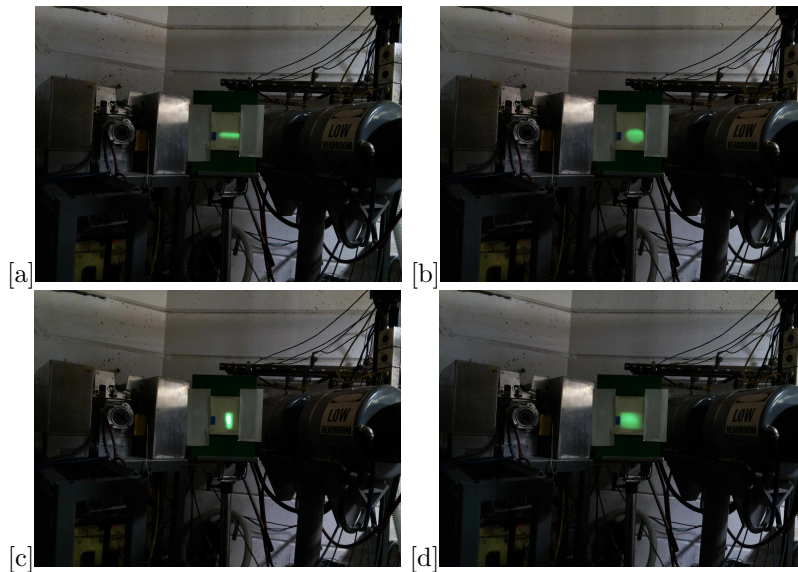


Figure 6: Various beam spot sizes as the quads bent the beam during the tuning process.

The Python program successfully controlled the quads and focused the beam. However, due to the wait time between running both codes, an issue arose regarding the time it took to send and receive commands from one code to the other. This minor error was fixed by adjusting the “sleep” time within each code. Due to the time constraints of the internship, the opportunity to run this experiment again and verify the full source of error in the Python program was unattainable.

8 Conclusions

To improve the overall quality and effectiveness of this experiment, the time dependencies between the two codes should be adjusted along with placing the raspberry pi and the phosphor screen on the same mount. Implementation of these adjustments will maximize the automation effects and speed up the calibration process during set-up.

CNL cyclotron operators have multiple devices to monitor and control. This automation project is the first step in replacing the analog controls used to tune the quads with the digital control that my program provides. Additionally, this project will serve as a tool in the automation of other beam lines and will enable future interns to incorporate the measurements of other beam parameters such as beam intensity and emittance.

The knowledge and experience gained from working at CNL will be applied to other lab work and research experiences I encounter throughout my career. Learning about accelerator physics, cyclotrons, and automation has broadened my perspective on possible career paths within physics.

9 Acknowledgements

I would like to thank Eric Prebys for allowing me the opportunity to work at Crocker Nuclear Laboratory. I would also like to thank Michael Backfish for providing me with the resources and guidance needed to complete this project. Thank you Tim Essert for working on the electronics, hardware, and electrical components of this project.

An additional thank you to the CNL staff, UC Davis Physics REU coordinators, and the NSF for offering the resources needed to succeed in this internship.

References

- [1] A. Rosebrock, “Practical Python and OpenCV + Case Studies”, PyImageSearch (2016)
- [2] D. Barak, B. Harrison, A. Watts, “Concepts Rookie Book”, Fermilab (2013)
- [3] E. Prebys, Accelerator Physics lecture Slides (2015)
- [4] <https://www.youtube.com/watch?v=drwruwiCqt8>
- [5] <https://www.youtube.com/watch?v=m2jp0k1ZHEE>
- [6] The Regents of the University of California Davis campus (2018, April 3), Crocker Nuclear Laboratory. Retrieved from <http://crocker.ucdavis.edu/>
- [7] Wikipedia contributors (2019, August 21). Cyclotron. In Wikipedia, The Free Encyclopedia. Retrieved from <https://en.wikipedia.org/w/index.php?title=Slavery&oldid=857306597>

- [8] Wikipedia contributors (2018, December 5). Quadrupole Magnet. In Wikipedia, The Free Encyclopedia. Retrieved from https://en.wikipedia.org/wiki/Quadrupole_magnet