

Optical Beam Profile Monitor for LENS Ion Source

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Abstract

There exists a need to conduct diagnostic tests for the LENS ion source at the Indiana University Cyclotron Facility. A pulsed proton beam of energy between 7 and 13 MeV with a peak current of 100 mA and a duty factor of 5% will be used to strike a beryllium target. In order to ensure that the beam is spread out enough as to not melt the beryllium target, a beam monitoring system will be developed and implemented about one meter upstream from the target material. Traditional monitoring devices are useless as they would melt if placed in the beam line. An attempt at duplicating a technique using CCD imaging to construct a beam profile of the low energy beam transport (LEBT) at 30 mA under cw operation and a measure of beam emittance has been performed. Future prospects involve implementing these methods to the full powered beam. Experimental setup, design and results are presented.

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1 Introduction

The Low Energy Neutron Source (LENS) at Indiana University Cyclotron Facility (IUCF) produces neutrons by striking a beryllium target with a proton beam. Protons are generated by the ion source, extracted with an energy of 25 keV and delivered to the RFQ by a low energy beam transport line (LEBT). The RFQ accelerates the protons to 3 MeV, and a DTL accelerates them an additional 4 MeV for a total of 7 MeV. Because of the low energy and high intensity, traditional interceptive beam line diagnostic tools melt if placed in the path of the beam. A non-interceptive method of constructing a beam profile and calculating beam emittance is desired in order to ensure safe operation of the beam. In addition to calculating the beam profile which gives one information regarding beam size, beam shape is also of interest. A single transverse beam profile measures a cross section of the beam, however it doesn't allow one to understand the spatial extent of the beam. An understanding about the size and shape of the beam is desired because the final interest is how intensely, and to what extent the beam is hitting the beryllium target. With a single beam profile, one wouldn't be able to tell the difference between a circular beam and a square beam with the same dimensions. However, these shapes are of interest as each would effect the target differently.

We sought to explore a means of calculating beam emittance as well as construct a beam profile by observing residual gas fluorescence with a CCD camera. Data was initially collected by observing residual gas at a pressure of 3.5×10^{-6} Torr. Later, data was collected by introducing *Xe* gas at a pressure of 10^{-5} Torr.

Problems involving lens distortion were neglected because only central pixels were considered in the final analysis. Other problems encountered during this experiment included eliminating scattered light from within the tube, as well as questions regarding the consistency of the camera placement.

Research was conducted to discover the feasibility of using tomographic methods from observations of residual gas fluorescence. Given multiple images taken from different angles of an object, one may reconstruct the shape of the object. Tomographic methods serve as a promising diagnostic tool for calculating the beam shape, and other laboratories are investigating this possibility[5]. Destructive diagnostics such as wire grids or flying wires allow one to gather information regarding beam shape in addition to spatial extent and profile

of the beam. This information isn't readily available from a single CCD image. In order to determine beam shape from CCD imaging, one needs to gather data from multiple angles around the beam line. Initially, we were interested in finding out if the same tomographic methods used in medical imaging (CAT-scans) could be easily implemented for this project.

2 Background

In order to fully understand the contents and setup of this experiment, a brief discussion of beam optics, emittance and tomography is important.

2.1 Emittance and Beam Optics

Emittance is a description of particles in phase space. Measuring the emittance of a particle beam serves as a diagnostic test for calculating beam transmission. Emittance serves as a tool to measure how much of the beam is being lost along the beam line. More precisely, emittance is defined as $\frac{\gamma \cdot \beta}{\pi}$ times the area occupied by the smallest ellipse that circumscribes particles plotted in trace space, where

$$\beta = \frac{v}{c}$$

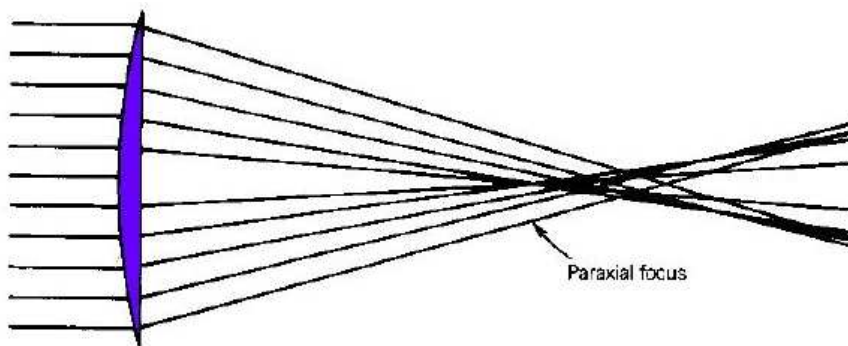
$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

c is the speed of light and v is the total speed of the particle.

In typical beam optics, z is always the beam direction. The coordinates x , y , x' and y' are used to describe the transverse position and velocity, respectively, of particles. Trace space is a plot of dx/dz vs. x whereas phase space is a plot of dx/dt versus x . However, for any beam energy and directional beam velocity, v_z , the slope measured in the x - z plane depends directly upon the transverse velocity. In order to be able to compare beam quality for accelerators of different energies, one multiplies the area of the ellipse in trace space by a factor of $\beta \cdot \gamma$ for normalization.

Ellipses are important for study because when one assumes a linear relation between restoring forces in beam line lenses and distance from beam axis, travel through a lens results in a rotation of the ellipse in trace space. Emittance is a monotonic function of beam location(z). When a beam is transported in a linear matter, emittance stays constant whereas when there are non-linear forces, emittance increases[3]. A beam which passes through an ideal solenoid would experience linear restoring forces. Accelerating a beam through a potential difference increases the velocity of particles and therefore is inherently a non-linear operation. For most applications, one desires a small emittance value.

The following illustration[1] serves as an example of a parallel beam being acted upon by a non-linear focusing lens:



Focusing elements in a lens with non-linear restoring forces tend to spread out the beam. A beam that is extremely spread out is of lower quality. The large focal point is apparent in this photograph.

2.2 Residual Gas Fluorescence

In an artificial vacuum chamber, there is always some residual gas leftover from what pumps are not able to remove. When beam particles hit these gas molecules, electrons are excited into an outer shell. When these electrons fall back into their stable lower shell, a photon is emitted from the gas molecule. Cameras allow one to focus the photons onto a CCD chip where the location and wavelength of the photon can be stored using digital technology. This is what makes analyzing a particle beam with a digital camera possible.

During the time period when the electron is excited, the nucleus of the gas molecule will move. If this drift time of the gas molecules is large, then there would be concern about the accuracy of positions measured from looking at the fluorescence light. Experiments

concerning the drift time of N_2 and Xe gas indicate that the drift times of these gases are negligible[4]. The research (Plum et al) indicates that typical drift time of N_2 molecules from a 400 keV proton beam is typically 60 ns whereas the drift times for Xe gas (two different wavelengths) is typically 6 and 51.5 ns. N_2 and Xe gases are convenient to use for imaging because the wavelengths of light emitted from their quantized excited states lie within the visible spectrum. When images are taken of residual gas, most of the light observed is emitted from N_2 molecules. The same researchers conducted experiments regarding drift times of N_2 and Xe gases when struck by protons of energies ranging between 1.4 to 25 GeV, and at a low pressure of 1.3×10^{-4} Torr. These results are important because not much research has been done with calculating drift time of Xe gas at such a low pressure. N_2 gas emitted predominantly light with wavelengths between 385 and 430 nm whereas Xe produced a broader range of light with wavelengths between 385 and 600 nm[4]. The research considered two different lifetimes for Xe : a strong component with a lifetime of 6 ns and a weaker component with a lifetime of 52 ns.

2.3 Tomography

Computed Tomography is the method used in CAT-scans to reproduce a 3-dimensional image of an object given multiple scans taken from multiple angles around an object. For the purposes of accelerator physics, in order to understand the shape, as opposed to the spatial extent of the beam from a 2-dimensional CCD image, an understanding and implementation of computed tomography is imperative.

Most literature about computed tomography focuses on x-ray tomography. Thousands of profiles are constructed by moving an x-ray source and/or detector through a 360° revolution and measuring the attenuation of the x-rays. For each angle θ , one can compute the radon transform:

$$P_\theta(t) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x, y) \delta(x \cos(\theta) + y \sin(\theta) - t) dx dy \quad (1)$$

The function, $f(x, y)$ represents the object in question. However, the desired computation is the inverse problem. Given a large number of projections, can one reconstruct the function $f(x, y)$. The Fourier slice theorem shows that it is possible to calculate the exact value given

an infinite number of angles, however there are methods of obtaining bounds for the number of necessary angles and precision.

The theory presented in [2] shows an equivalence between equation (1) and the 2-dimensional Fourier transform of $f(x, y)$:

$$F(u, v) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x, y) e^{-2\pi i(ux+vy)} dx dy \quad (2)$$

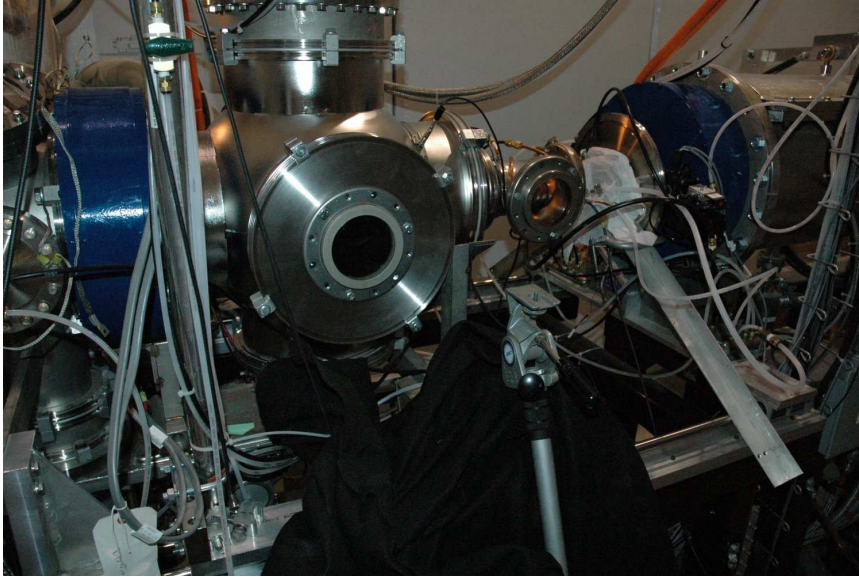
The use of techniques derived from these transforms require a large number of images in order to be successfully implemented. It appears as though the techniques currently being used in medical imaging may not be useful for applications in accelerator physics. However, another method known as Algebraic Reconstruction Technique (ART) is what current researchers are investigating. In this method, one sets up an array consisting of unknown variables which cover the object of interest. Then one proceeds to solve for these unknowns through the use of algebraic methods. In contrast to the transform based methods, this procedure can become numerically cumbersome and is not as precise. However, given that accelerator physicists would like to use extremely few pictures, this may prove to be the more promising of the two tomographic methods.

3 Experiment

We analyzed a 30 mA cw 25 keV proton beam in the LEBT section. The vacuum chamber viewed was painted black to eliminate internal light reflection, and a tungsten beam stop was water cooled in an attempt to eliminate light from being produced downstream. Pictures of graph paper were taken in order to do a distance calibration of the camera for various zoom settings and distances.

3.1 Data Acquisition

A picture of the ion source and camera placement is shown in the following figure:



Ion Source and Camera Setup

A Nikon D70 camera (not pictured) was mounted on a tripod, 28.4 cm from center of chamber. Black cloth was wrapped around the camera and covered the window around the camera in order to eliminate scattered light in the room from reaching the camera.

The variable parameters used in collecting data included the following: solenoid current, gas pressure, shutter speed, focusing and f-stop number. The most useful parameters to change were the solenoid current and shutter speed, other parameters were either kept constant or were a choice between observing Xe or N_2 gas.

The parameters that were held constant included pressure, f-stop and zoom. Xe gas pictures were taken at a constant pressure of 1×10^{-5} torr whereas residual gas pressures were held at a constant pressure of 3.5×10^{-6} torr. From observing previous pictures of grid paper, it was found that a zoom setting of 22 mm gave a relatively undistorted image. Some pictures were taken with the zoom pulled all the way back to 18 mm in order to have the camera flush against the window, whereas other pictures were taken with a 22 mm zoom in order to reduce distortion. With a more secure mounting device one would easily be able to accommodate any camera in order to reduce the amount of distortion.

In order to obtain a visible image, a shutter speed greater than $\frac{1}{5}$ seconds and a f-stop number larger than 4 was required. Pictures with a shutter speed larger than 5 seconds

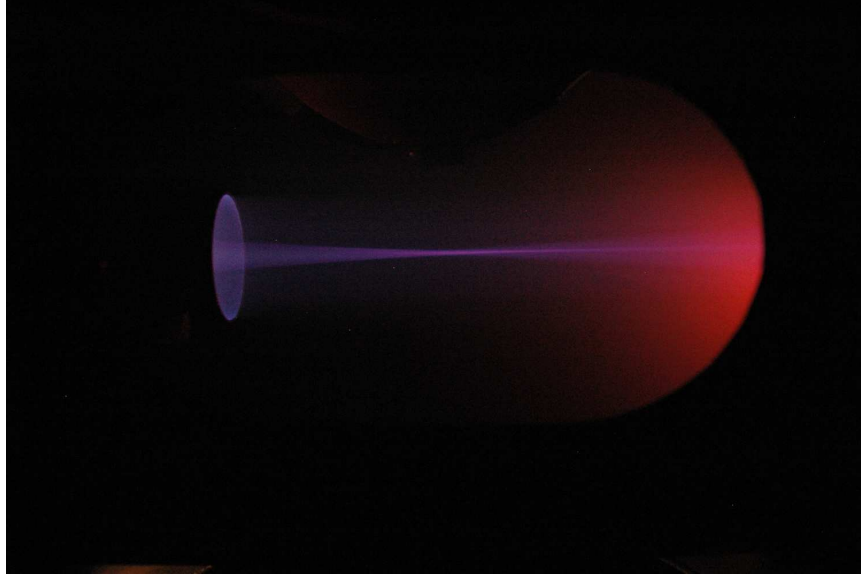


Figure 1: This is a picture of the residual gas fluorescence initiated by the beam. The black oval outline the edges of the port hole and the colored oval on the left side of the picture is the beam pipe. The red light on the right hand side of the picture is produced by protons hitting the walls of the beam pipe downstream from this chamber.

collected too much reflected light from within the chamber to be useful. We present the results from a picture (Figure 1) taken with the following settings:

$$\begin{aligned} \textit{Lens Current} &= 170\textit{Amps} \\ \textit{F - stop} &= 4 \\ \textit{Shutter Speed} &= \frac{1}{1.6} \textit{Seconds} \\ \textit{Extraction Current} &= 28.9 \textit{mAmps} \\ \textit{Residual Gas Pressure} &= 3.5 \times 10^{-6} \textit{Torr} \end{aligned}$$

The interesting data points were in the center of the image, so a square of data points from the center of the larger image were chosen for analysis. Figure 2 is an image of the blue color intensity values. Only these colors were analyzed, although including red and green values would have been a trivial matter.

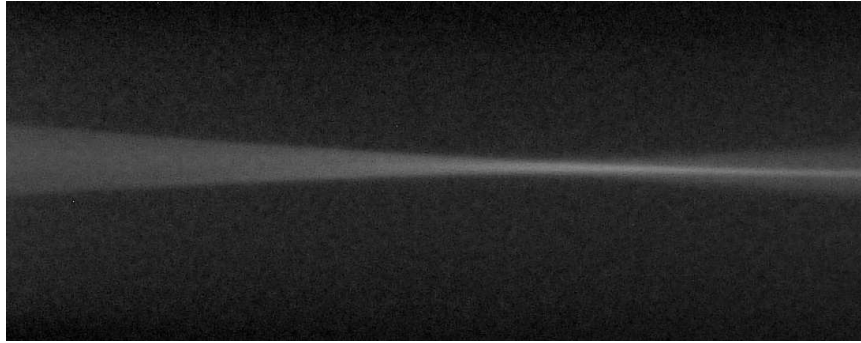
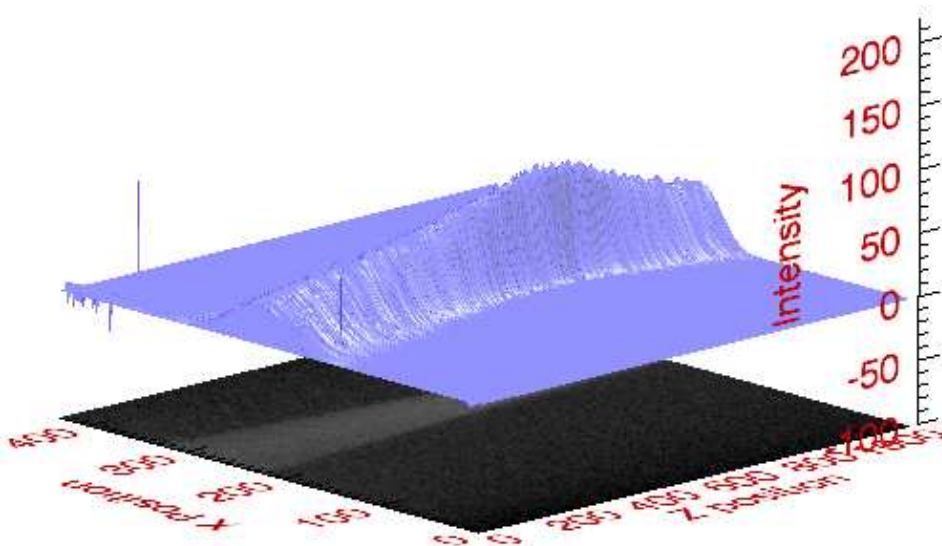


Figure 2: Black and white image of blue intensity values. Color images use RGB (red, green blue) color values, so we had to make a choice about which colors and what percentage of those colors we should use. It didn't appear to make a difference if red and green intensities were omitted.

3.2 Data Analysis

The IDL image processing program was used for all data analysis. IDL was able to smoothly import information from digital images. Intensity values could be read off given any location (i, j) on the large array, and surface plots give one an idea about the size of the beam. As an illustration of IDL's flexibility, the following surface plot of fitted gaussian functions were plotted above the original image:



Gaussian Surface Plots above 2D Image

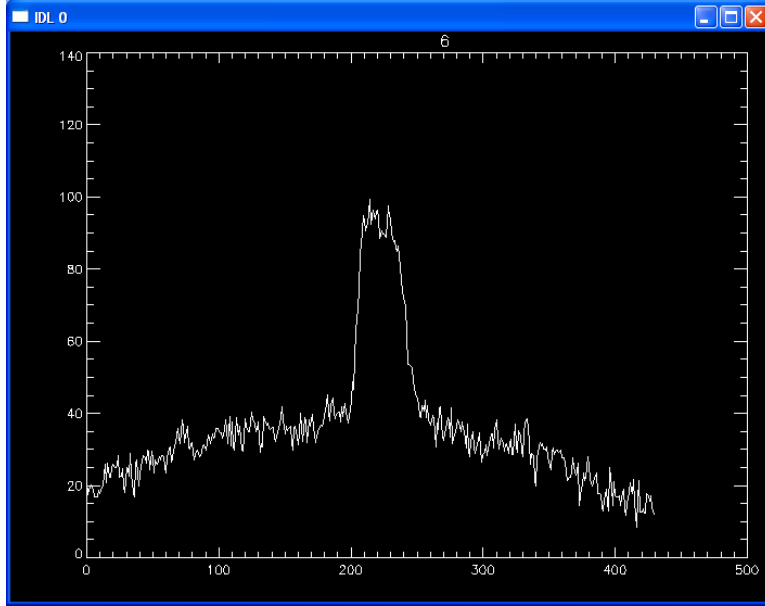


Figure 3: Transverse Profile: Intensity vs. X position

In order to calculate emittance one needs to have a method of calculating distances. A picture of grid paper was taken with lines printed at spacings of 0.5 cm apart. A simple program was written to calculate the pixel location of grid lines. An averaging routine showed that 42 ± 3 pixels corresponded to 0.5 cm. Central pixels were spaced farther apart whereas outer pixels were closer to 39 pixels per grid line. It was assumed that 83 pixels = 1 cm for the image we analyzed.

Best fit curve of the form given in equation (3) was fitted to the data using a fitting routine implemented in IDL. The quadratic term estimated the H_2^+ , H_3^+ ions as well as background noise. A typical transverse intensity plot is shown in Figure 3.

$$f(x) = A_0 \cdot e^{\frac{-(x-A_1)^2}{2 \cdot A_2}} + A_3 + A_4 \cdot x + A_5 \cdot x^2 \quad (3)$$

For a 25 keV proton beam where one assumes $\gamma \approx 1$, β is calculated from the following equation:

$$K.E. = \frac{m_p v^2}{2} \quad (4)$$

This implies:

$$v = \sqrt{\frac{2K.E.}{m_p}} \quad (5)$$

For a 25 keV proton beam:

$$\beta \equiv \frac{v}{c} \approx 0.0073 \quad (6)$$

A calculation of the emittance $= \gamma \cdot \beta \cdot \epsilon$ is determined by the following equation:

$$\epsilon = \sqrt{\det \sigma} \quad (7)$$

Where

$$\sigma \equiv \begin{bmatrix} \sigma_{11} & \sigma_{21} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} = \epsilon \begin{bmatrix} \beta & -\alpha \\ -\alpha & \beta \end{bmatrix} \quad (8)$$

and α , β and ϵ are the usual twiss parameters.

Given the radius and distance between three different profiles in drift space, one can calculate the emittance fairly easily[3]. An application of the standard drift matrix yields the following equations[3]:

$$\begin{aligned} R_1^2 &= \sigma_{11} \\ R_2^2 &= \sigma_{11} + 2L_1\sigma_{12} + L_1^2\sigma_{22} \\ R_3^2 &= \sigma_{11} + 2(L_1 + L_2)\sigma_{12} + (L_1 + L_2)^2 \sigma_{22} \end{aligned}$$

Where σ_{ij} are elements of the σ matrix as measured at the location of the first radius[3]. In general, beam widths are chosen as to encompass 90% of the beam. In our analysis, standard deviation values of the gaussian fits were chosen as the beam widths.

The calculated emittance for the picture analyzed in IDL yields a value of 0.268π mrad mm. Although this figure is higher than expected, it was verified by hand by picking out points on the image. The focal point was estimated to have a width of 2.53 mm, and points were chosen along the edge of the beam in order to calculate slopes. The value reported by this method was 0.248π mm mrad.

4 Conclusion

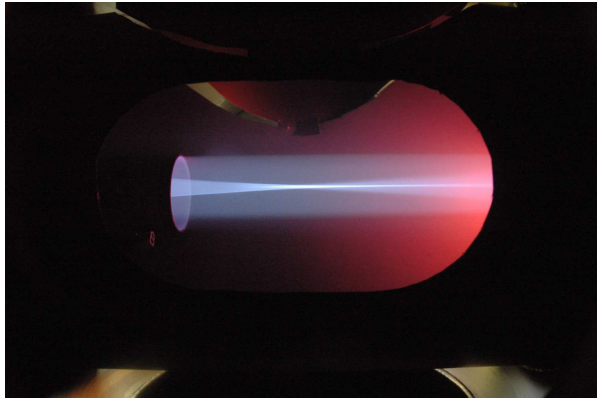
Constructing beam profiles from observations of residual gas fluorescence proves to be a promising method of performing beam line diagnostics. Beam emittance can be inferred from a digital photograph of the fluorescent light emitted from the beam. The results from this project have shown that problems involving lens distortion and camera placement still need to be dealt with. We were unsuccessful in implementing tomographic methods given the short time span of the project.

Acknowledgements

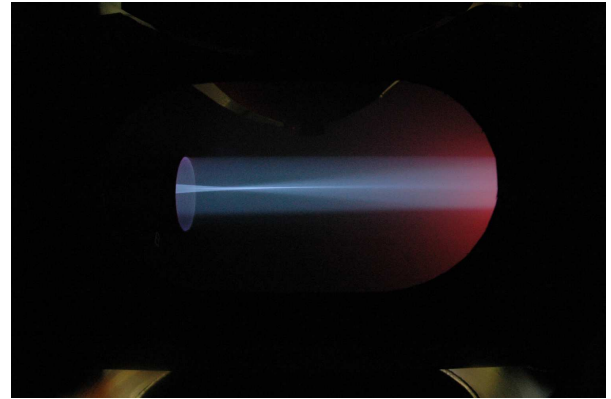
I would like to thank my advisors Laddie Derenchuk and Keith Solberg for sharing their knowledge and teaching me about accelerator physics. I would also like to thank the REU coordinators, Andy Bacher, John Carini and the National Science Foundation for giving me the opportunity to be a part of Indiana University and experience hands on research. Also, I would like to thank all the REU students for making this summer so enjoyable and being willing to discuss physics... anytime... anywhere.

A Appendix

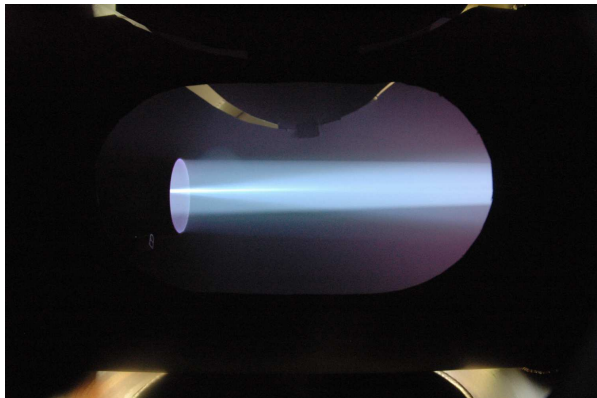
The following sequence of pictures illustrate various focusing strengths when current in the solenoid is varied. All pictures were taken with Xe gas inserted into the chamber at a pressure of 1×10^{-5} torr. The first picture at a current of 170 mA focuses the H^+ ions at the center of the chamber. As the current increases the larger H_2^+ ions are focused at the center of the chamber and the H^+ ions diverge before they enter the chamber.



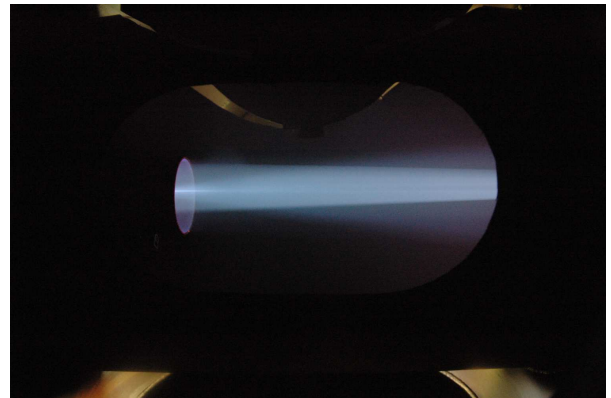
170 mA



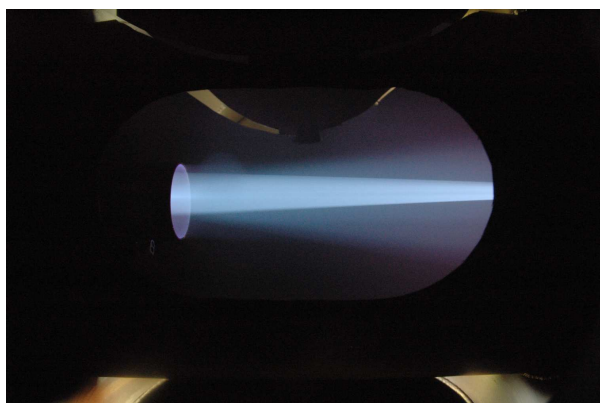
180 mA



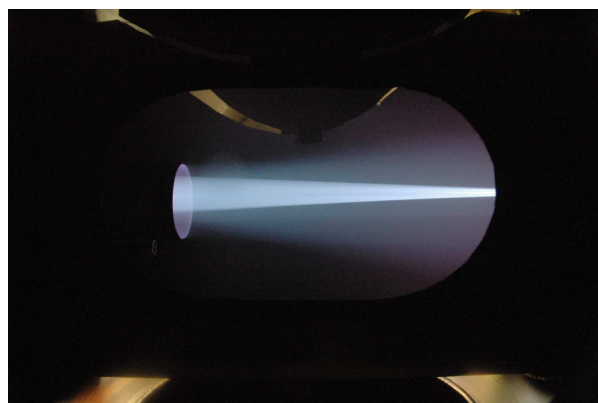
190 mA



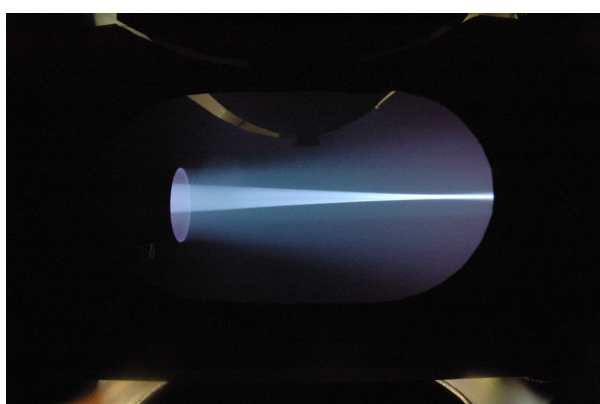
200 mA



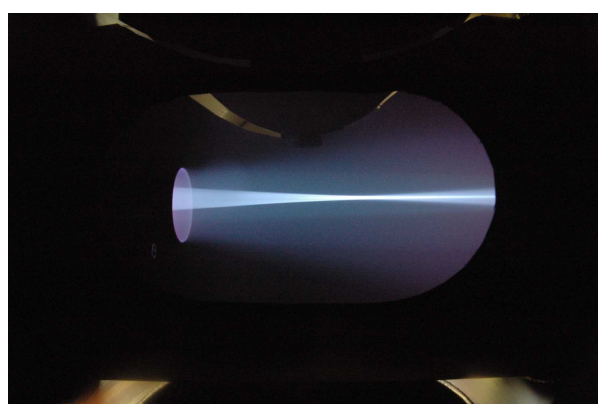
210 mA



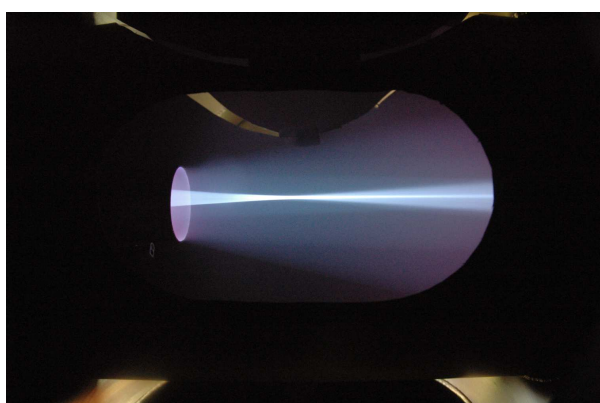
220 mA



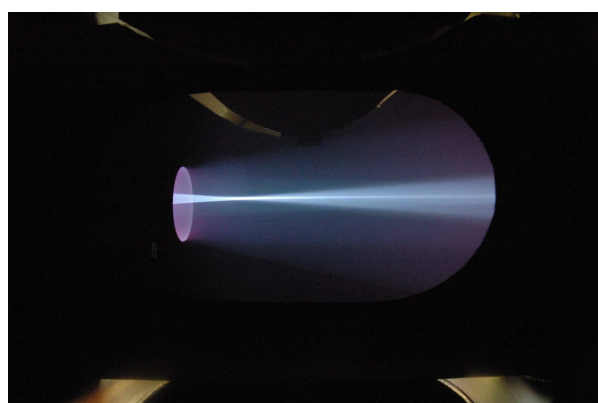
230 mA



240 mA



250 mA



260 mA

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