UNDERGRADUATE REPORT

Dynamics of Particle Accelerators

by Robert Courtney
Advisor:

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Robert Courtney
University of Maryland ISR

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REU Program for Undergraduates

The problem description given to me at the beginning of the summer stated that my project would include "…modeling, analysis & simulation of particle beam dynamics for a low speed particle accelerator that has been developed at the university." The description goes on to state "The student will learn about dynamic modeling & analysis of particle accelerator beams as well as experimental issues in data gathering." My graduate student advisor and I decided the best way to accomplish these goals was to develop a computer simulation of the particle beam and compare my simulated results to experimental results using the actual University of Maryland Electron Ring.

Simulation

To develop a simulation of the particle beam I had to learn how to program effectively using Matlab and the built in program Simulink. Matlab is a programming language with many applications in the field of Engineering. Simulink is a visual interface used to model complex systems by utilizing block diagrams rather than computer coding language. I spent several weeks going through tutorials on both of these programs and practicing creating models.

The simulation I developed is based on the KV equations that my graduate student advisor Chao Wu gave me. The KV equations are two coupled, second order, nonlinear differential equations. They are as follows

$$\frac{\partial^2 X}{\partial s} = -\kappa_x X + \frac{2K}{X+Y} + \frac{{\varepsilon_x}^2}{X^3} \quad (1)$$

$$\frac{\partial^2 Y}{\partial s} = -\kappa_y Y + \frac{2K}{X+Y} + \frac{{\varepsilon_y}^2}{Y^3} \quad (2)$$

(Wu 1). In these equations *s* is the direction the beam is traveling while X and Y are the 2xrms beam radii perpendicular to *s* (Wu 1). K is the generalized dimensionless perveance and equals $(\frac{I}{I_o})(\frac{2}{\beta^3\gamma^3})$ where $I = .024A, I_o = 17mA$, $\beta = \frac{v}{c}$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, and $v = 5.8\cdot 10^7$ (Wu 2). The variables ε_x and ε_y are the emittances and equal $30\cdot 10^{-6}$. κ_x and κ_y are the external focusing and defocusing elements (Wu 2).

The physical significance of each of these variables is important in understanding the simulation. The emittance of the beam is a measure of the volume of space the beam occupies (Orthel 58). The generalized dimensionless perveance is measure of the magnitude of space charge effects on the beam (Orthel 58). Space charge forces occur when charged particles, in this case electrons, are close enough to each other that their like charges repel the particles around them. The effects of space charge are seen most in beams with low emittance. The external focusing and defocusing elements arise from the quadrupoles and dipoles, which steer the beam and counteract space charge effects.

The Accelerator ring in the simulation is made up of 18 different FODO sections. Each FODO has the same structure; there are two quadrupoles with a drift section following each quadrupole (Wu 2). The length of each quadrupole is 0.037m and the length of each drift section is 0.123m. The actual UMER contains 36 FODO sections but for design purposes the simulation cuts that number in half. The variables κ_x and κ_y are varied along each quadrupole and have values of:

First Quadrupole:	$\kappa_x = -221.8$	$\kappa_y = 225.6$
Drift	$\kappa_x = 0$	$\kappa_y = 0$
Second Quadrupole	$\kappa_x = 225.6$	$\kappa_y = -221.8$
Drift	$\kappa_x = 0$	$\kappa_y = 0$

To model the changing forces in my simulation I used a signal that varies with *s*, where *s* is the distance traveled around the circumference of the ring. The block diagram of the Simulink simulation can be found in figure 1.

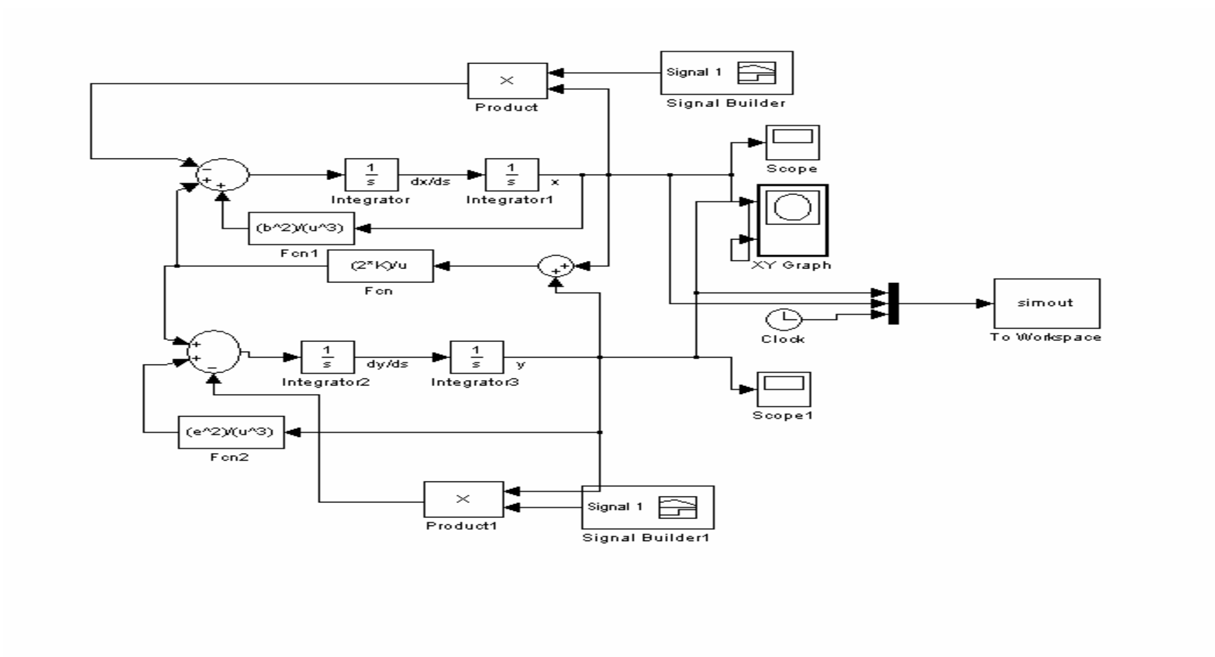
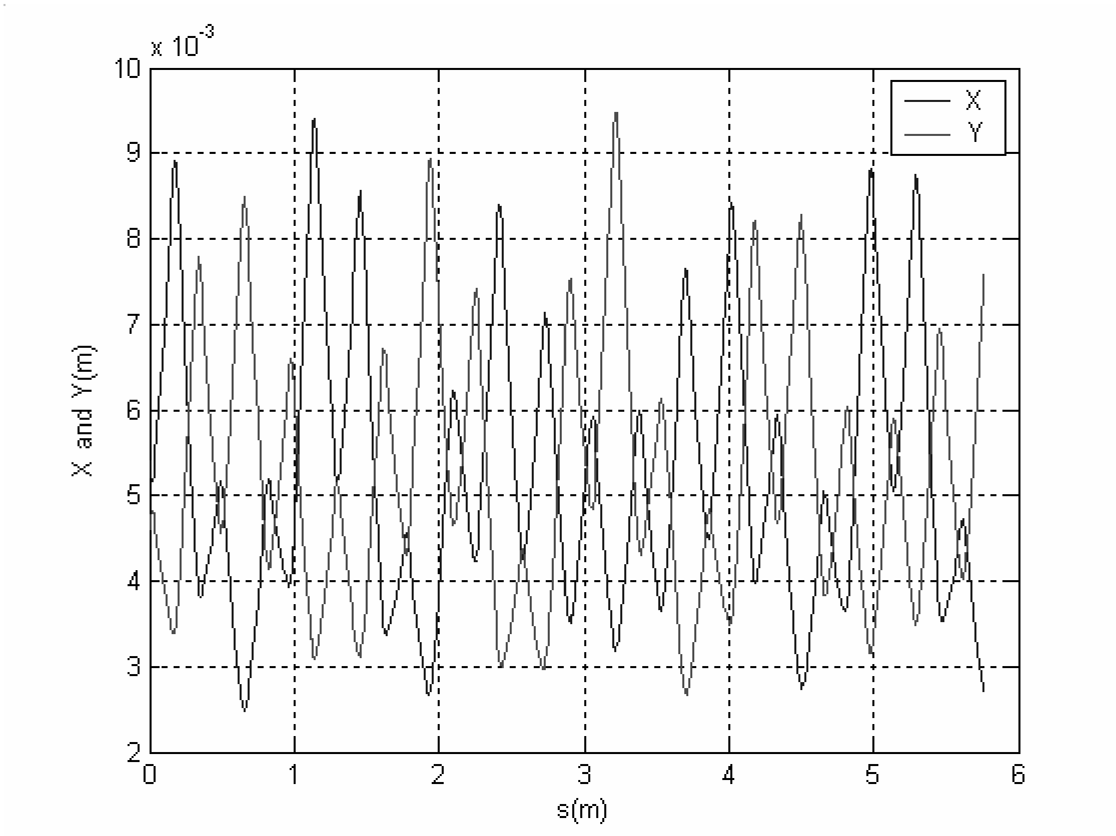


Figure 1: Simulink Block Diagram of KV Equations

Graph 1 contains a plot of the values of X and Y versus *s*.



Graph 1: Simulation Results for X and Y versus s.

The graph shows that the beam should have an elliptical shape as it travels around the ring because there is a general pattern where the X values are large when Y values are small and vice versa. The actual system is much more complex than the equations this simulation is based on, so an exact match between this data and experimental data is not expected. Chao Wu created a simulation using Matlab coding language which yielded equivalent results to my Simulink model.

Introduction to UMER Experiment

The University of Maryland Electron Ring has several features that make it useful for experiments. The Ring has a circumference of 11.52m which is made up of 36 FODO sections of length 0.32m (Reiser et al. 235). Each FODO is made up of two printed circuit quadrupoles for beam focusing and 1 printed dipole for steering (Reiser et al 235). The particle beam is sensitive enough so that the earth's magnetic field has an effect on its path. The UMER ring uses a Helmholtz coil to counteract this problem (Reiser et al 234). The beam also has three induction gaps that help prevent erosion of the beam due to space charge forces (Reiser et al. 234). The characteristics of UMER allow it to investigate phenomenon resulting from highly space-charge dominated beams as well as beam types found in more typical accelerators (Reiser et al. 234). A photo of the UMER can be found in figure 2. For more details on the UMER or on beam physics go to the UMER webpage.

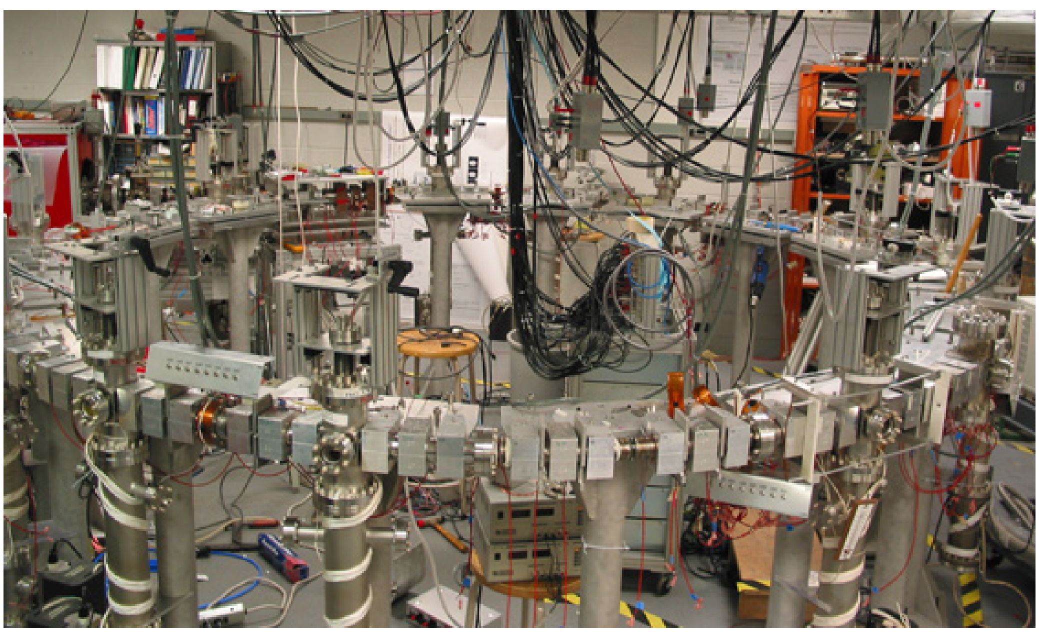


Figure 2: Photo of UMER ring (http://www.umer.umd.edu/).

Experimental Procedure

The Goal of my experiment is to use the phosphor screens located around the ring to capture images of the beam. The screens can be moved in the path of the beam by using an actuator (Li 9). The mechanical systems that raised and lowered the phosphor screens were fragile and broke down at two places, RC11 and RC13. Luckily this did not have a large effect on the experiment. A mirror on the outside of the ring reflects the picture to a camera which records the image (Li 9). The beam was set at the same settings as the simulation so the results would be comparable. To take each picture a phosphor screen was placed in the beam path while making sure that no other screens were down at the same time. At this point the accelerator gate would be opened and the beam turned on. Before taking each picture the camera had to be covered with a black cloth so no external light interfered. An image of the beam was projected on a television screen and captured using photo imaging software. These steps were repeated at the following locations: RC1, RC5, RC6, RC7, RC9, RC12, RC15.

Data and Graphs

To analyze the photographs of the beam I used “umerctrl” by Hui Li, an image processing program. From each image umerctrl can calculate the beam radii in the x and y directions. Figure 3 contains the images of the beam at the different phosphor screens.

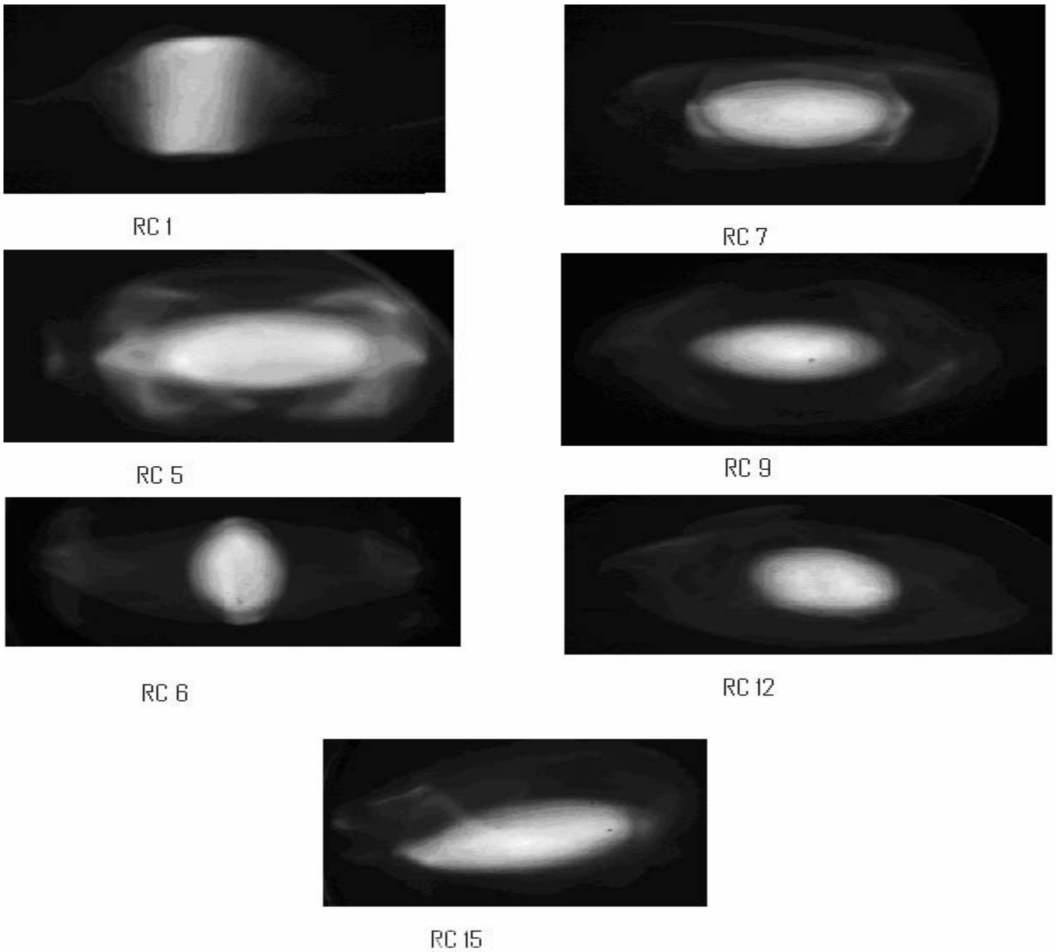


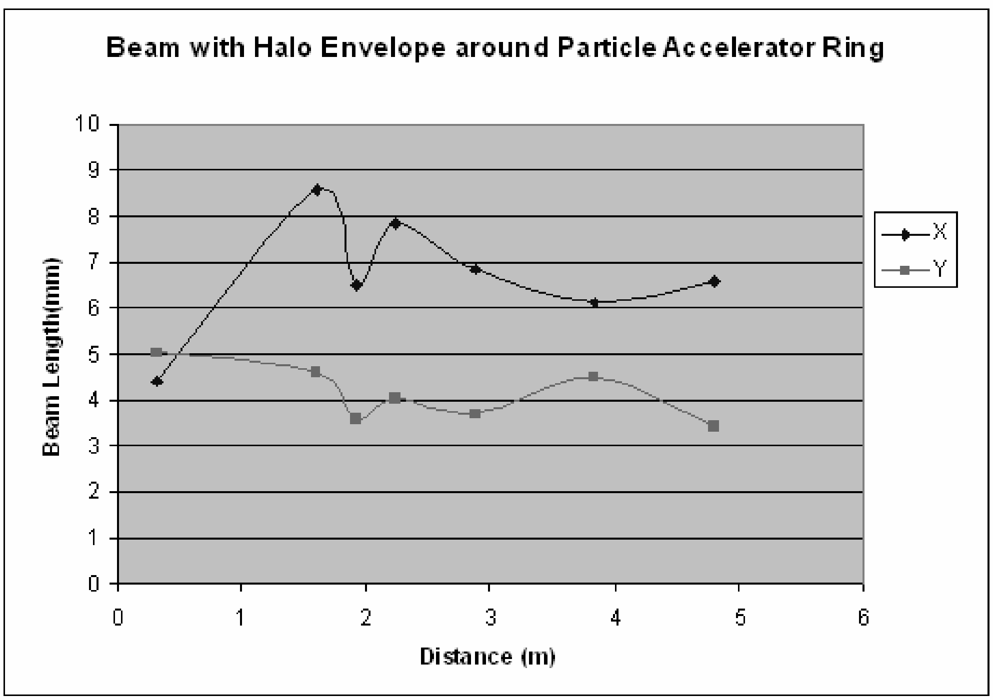
Figure 3: Beam Images

Looking at the photos there is a region around the outside of the beam core that appears lighter than the central core, this is the beam halo. According to Fedotov; "…beam halo is just some number of particles of any origin which lie in the low-density region of the beam…"(qtd. in Wei et al. 3). Without going into too much detail the formation of halos usually results from a combination of several factors. Most common mechanisms that generate halos in ring shaped accelerators are space charge effects, rf noise, and problems resulting from injection and multiple turns (Fedotov qtd. in wei et al.

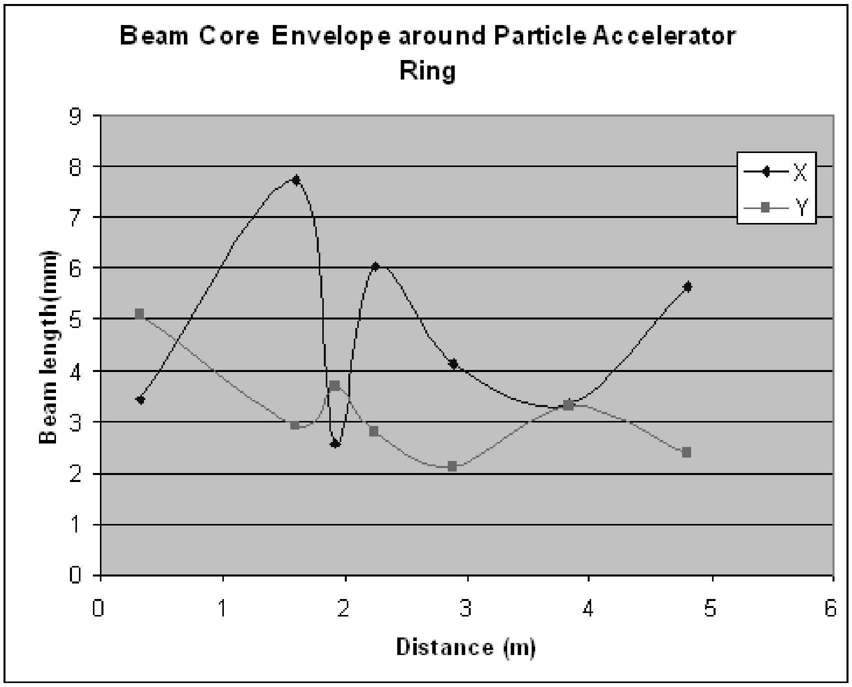
3-5). Beam radii data with and without halo can be found in table 1. Plotting the X and Y radii data against each other gives graphs 2 and 3. Graph 2 includes the beam halo in its calculation while graph 3 uses only the beam core data.

Including Halo	x (mm)	y (mm)	Beam Core	x (mm)	y (mm)
RC1	4.42	5.02		3.45	5.11
RC5	8.57	4.6		7.74	2.91
RC6	6.52	3.58		2.57	3.69
RC7	7.82	4.03		6.03	2.81
RC9	6.86	3.68		4.14	2.11
RC12	6.14	4.5		3.33	3.32
RC15	6.58	3.43		5.66	2.38

Table 1: Beam core radii and beam halo radii data

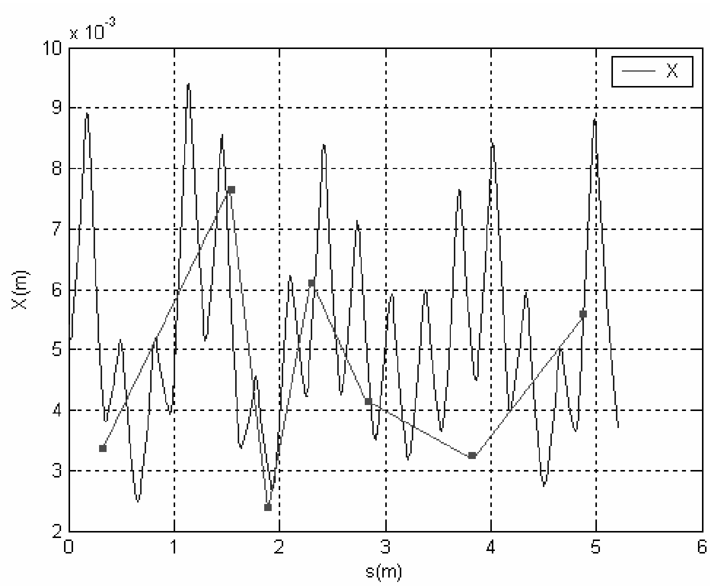


Graph 2: Experimental data for Beam including Halo radii

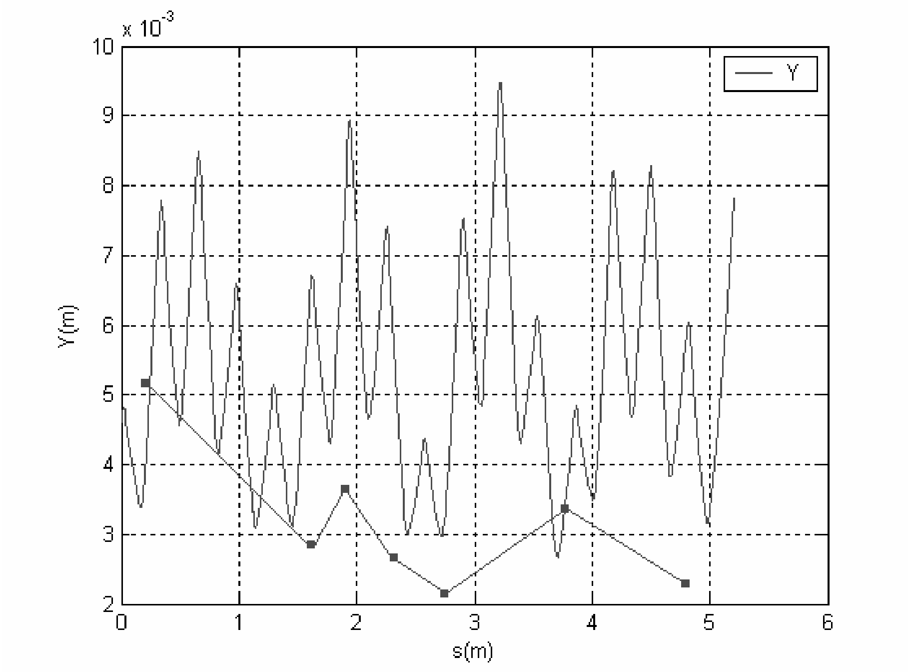


Graph 3: Experimental data for beam core radii.

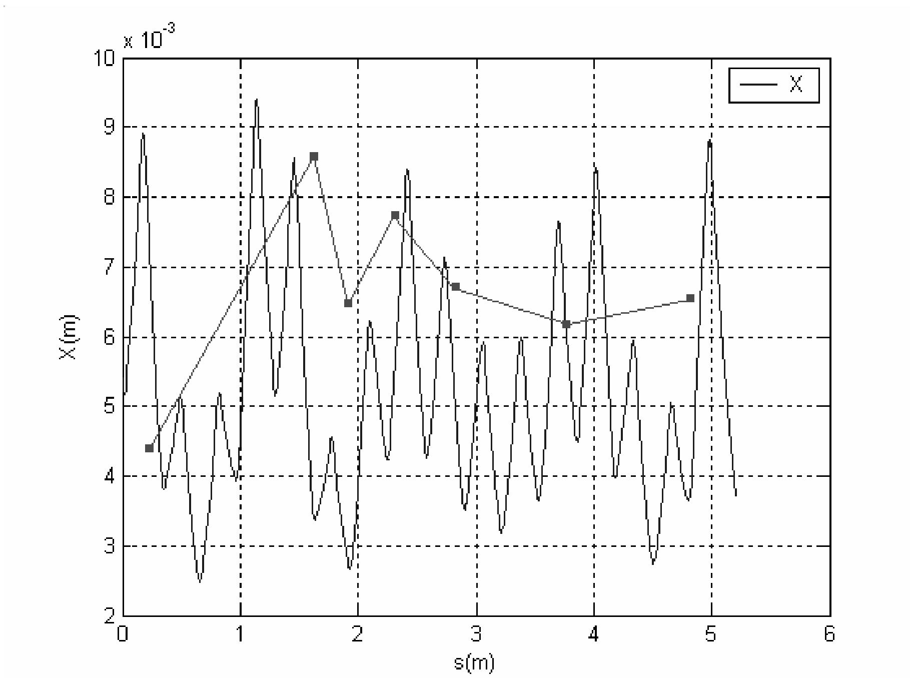
Graphs 4, 5, 6 and 7 contain the experimental data plotted on the same axis as the simulation data. The blue or red lines represent the simulated data and the green lines represent the experimental data. For clarity only the x or y direction is compared on each graph.



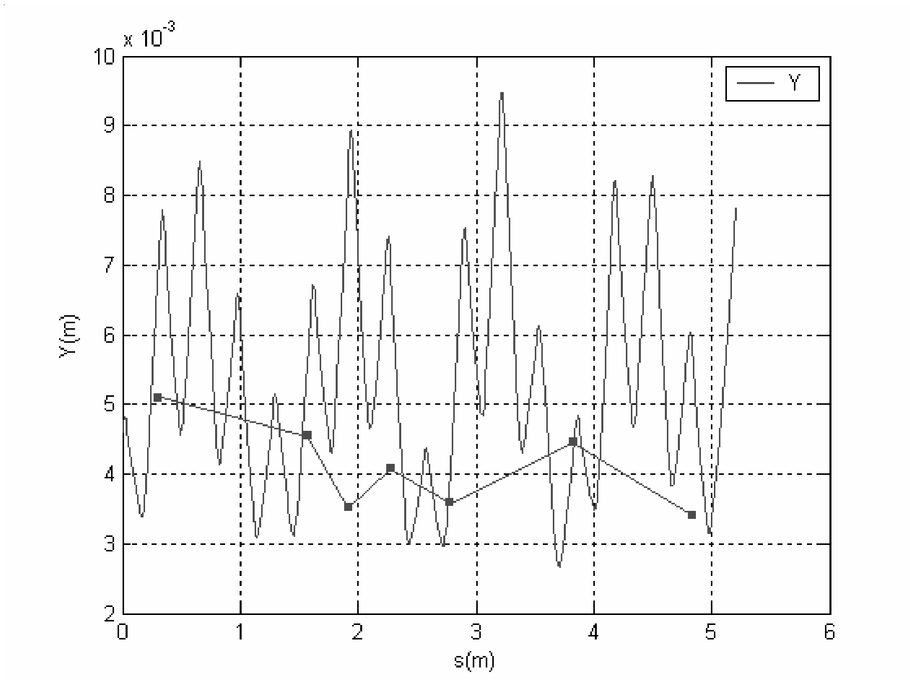
Graph 4: X Direction beam core comparison



Graph 5: Y Direction core comparison



Graph 6: X Direction halo Comparison



Graph 7: Y Direction halo comparison

Discussion

Looking at the beam pictures taken from the camera the shape of the beam is elliptical. The graph of the data taken from the beam imaging software confirms this. The experimental data shows that for the most part the magnitude of the x and y radii vary inversely. The simulation of the KV equations using Simulink also predicted this shape. It is unclear whether or not including the halo in the calculation of beam radii provided a closer match to the simulation.

Because of the limitations on the number of pictures taken due to time and equipment restraints the experimental set of data has a very small sample size. If this experiment was replicated with a larger set of processed images the simulated graphs would match up more closely with the experimental results. Another reason for the difference between simulated and experimental figures results from the simplicity of the simulation. The KV equations used do not take into account many of the variables that affect the path of the beam. With more time and a better understanding of particle physics a more accurate simulation could be developed that provides a closer match to the laboratory measurements. In addition, the UMER is still undergoing modifications and construction, so there will be some variance in its results.

Overall the summer project was a success. I performed an experiment using state of the art equipment that I would not otherwise have had the chance to do. In addition the experience I have using Matlab and Simulink will be useful for my future career in engineering. Chao Wu and Dr. Abed helped to teach me the basics of control theory, which will help when I take a course on it next year. Special thanks go to Dr. Santiago Bernard and Dr. Rami Kishek who both provided help and guidance during the UMER experiment.

Works Cited

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