Initial Design and Testing of the Flat Plasma Spectrometer

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Abstract

The Flat Plasma Spectrometer (FlaPS) is an instrument that may be used to measure the kinetic energy and angular distributions of ions in the space environment. Development of a prototype FlaPS model is a key in knowing how the system will operate in the space environment. Use of software with which one can simulate the geometry of the FlaPS system and "fly" ions through the system provided necessary information for the construction of the FlaPS prototype. Once the prototype was constructed several tests were performed using an ion beam apparatus. These tests revealed potential problems in the initial design of the FlaPS system; remedies are currently being investigated.

INTRODUCTION

Scientific analysis of space has been of interest for centuries. Advances made in this field in resent decades have been astounding and scientists, primarily working through the National Aeronautics and Space Administration, NASA, continue to search for information which will enhance our general understanding of the space beyond the surface of the earth. A recent project proposed by NASA involves a system using one primary and several secondary satellites to measure certain cosmospheric parameters. This system consists of about a dozen small satellites set in eccentric orbits around the earth, orbits that come very close to the earth at their apogee. A primary satellite would follow a nearly circular orbit, staying relatively close to the earth, with the secondary, smaller satellites "communicating" with the primary satellite when the two are in close proximity. Each of the secondary satellites would perform a specified function, and each would be kept small. Because the secondary satellites are small, they could provide only about 700 W of power, much less than a typical satellite, and hence are not capable of transmitting the data they collect to earth. The primary satellite provides the solution to this problem. Each small satellite transmits the data it has collected to the larger satellite when their orbits approach one another. The primary satellite, by means of a larger power source, would transmit the data collected from the secondary satellites to earth.

The data collected by the secondary satellite would include information about the plasma sheath that surrounds the earth. Scientists are interested in measuring the kinetic energy spectra of the ions in the plasma in order to understand, for example, the connection between the sheath properties and solar magnetic storms.

The technology required to operate the secondary satellites is available. Miniaturized power supplies that provide high voltages to the secondary satellites are available. However, the manner by which the collected data will be transmitted to the primary satellite and subsequently transmitted to earth remains unclear, although the use of current cell-phone technology looks promising.

A “Flat Plasma Spectrometer” currently being developed by the Johns Hopkins University Applied Physics Laboratory and the Atomic Physics Laboratory of the College of William and Mary will provide a prototype of an energy analyzer which could, ultimately, be used as an instrument on one of the secondary satellites. The purpose of the Flat Plasma Spectrometer (FlaPS) is to measure the kinetic energy spectra of ions in the space environment for energies ranging from 10eV to 5 keV. The FlaPS system is designed to occupy a volume on the order of several cubic centimeters and is characterized by a high throughput-to-volume ratio, making it an ideal component for one of the small-scale secondary satellites.

THE FLAT PLASMA SPECTROMETER – INITIAL DESIGN

The Flat Plasma Spectrometer is capable of measuring the kinetic energy and angular distributions of ions in the space environment. It consists primarily of four parts: the collimator, the deflector, the mask, and the detector. Figure 1 is a schematic diagram illustrating the initial iteration of a design for the FlaPS system.

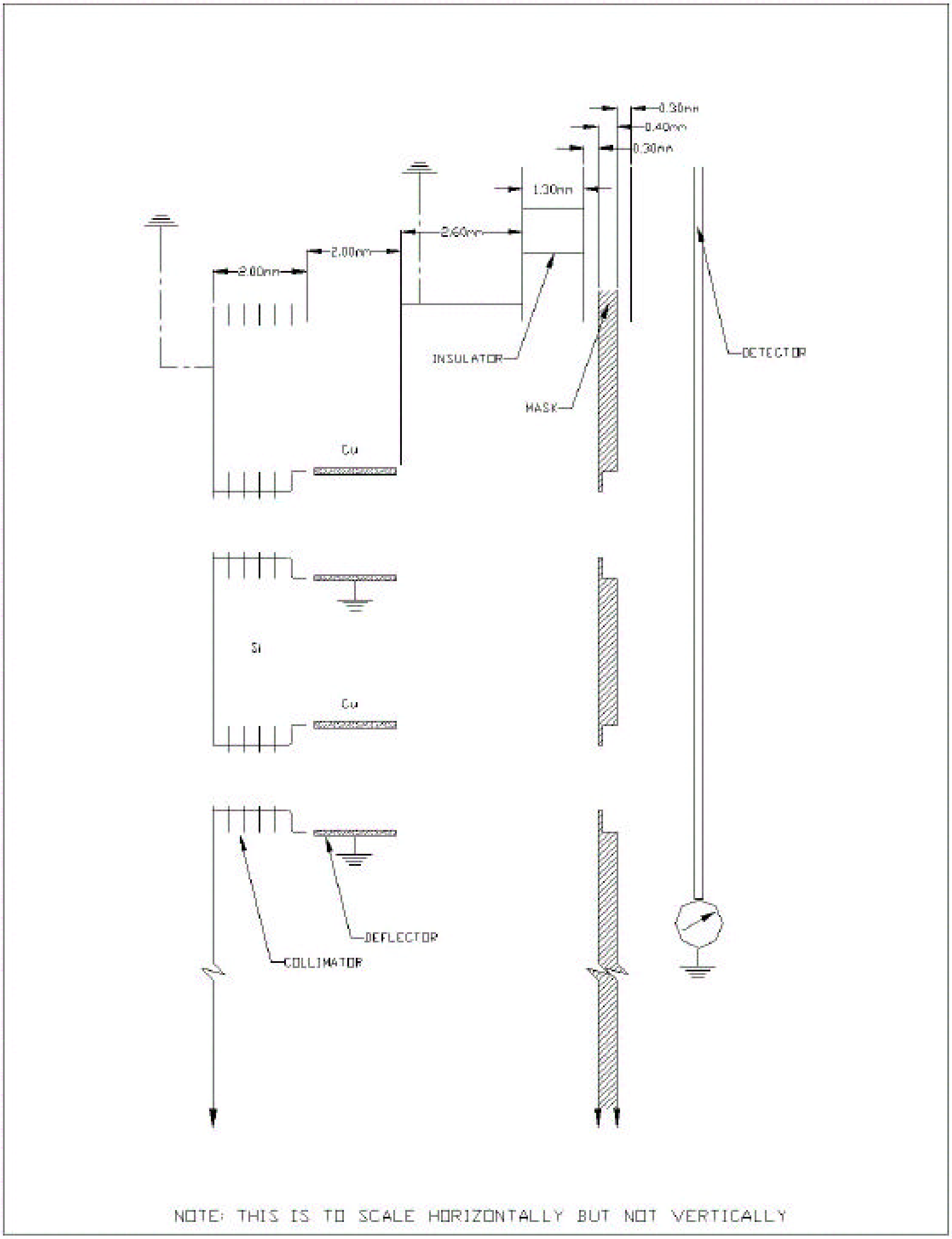

Figure 1 – Initial Design of the FlaPS System

In the following we will describe the salient features of the prototype versions.

The ions enter the FlaPS system through the collimator. The collimator consists of a stack of five silicon apertures. The silicon used in these apertures is n-doped, making the silicon act as a semi-conductor with a resistivity of approximately 5-15 Ωcm. Because the silicon acts as a semi-conductor it allows charged particles to arrive at its surface and then flow from the surface without charging the surface. As the face of the silicon apertures will be bombarded with charged particles, the semi-conductivity of the silicon is essential.

Each silicon aperture consists of two layers. The top layer has holes that have been etched through it in a configuration of five columns of holes with ten holes per column. These holes are 140 μm square and separated by a distance of 400μm vertically and 800μm horizontally, and are etched through the surface of the silicon apertures using a technique called deep reactive ion etching (DRIE) (Champion et al., 6). The bottom layer has holes with a width of 300μm centered on the 140μm square holes of the top layer. The total thickness of the collimator is 2mm. In the space environment the collimator will be exposed to atomic oxygen that causes a surface coating oxide. The oxide coating would make the collimator susceptible to static charge accumulation. To avoid this effect each silicon aperture would be coated with gold (Champion et al., 6.) Figure two shows the collimator in detail.

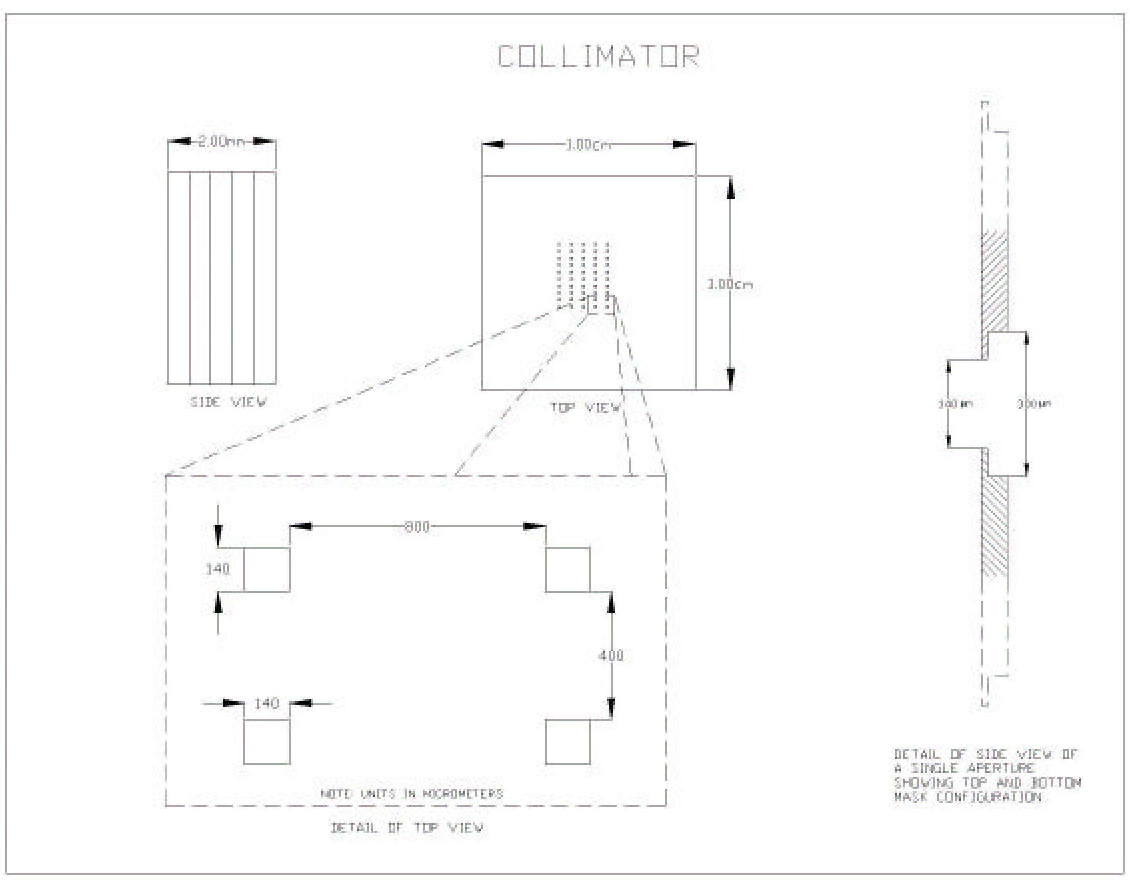

Figure 2 – The Collimator

The deflector plate consists of interweaving copper electrodes with a thickness of 2mm. The width of the deflector was originally 2mm and later changed to 1mm. The reason for this change will be discussed later. The deflection of the ion beam is possible by changing the voltages of the deflector plates. Figure 3 shows the deflector arrangement in detail.

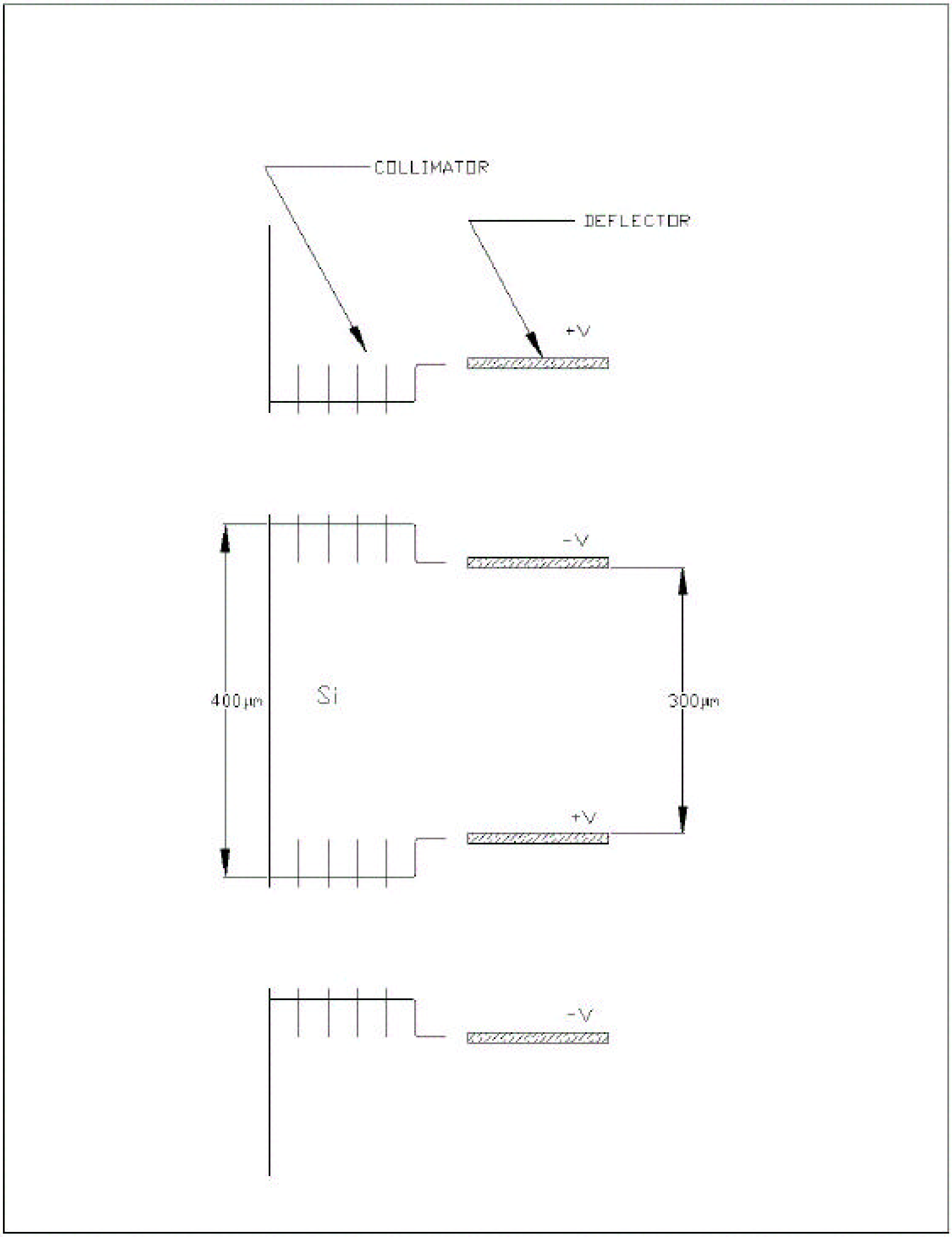

Figure 3 – The Deflector

The mask is a prototype of one of the silicon apertures of the collimator. The mask is located at a distance of 3.2mm from the deflector plates, and it is at ground potential. When no voltage is applied to the deflector plates the ions will pass directly through the corresponding hole in the mask, as may be inferred from figure 4.

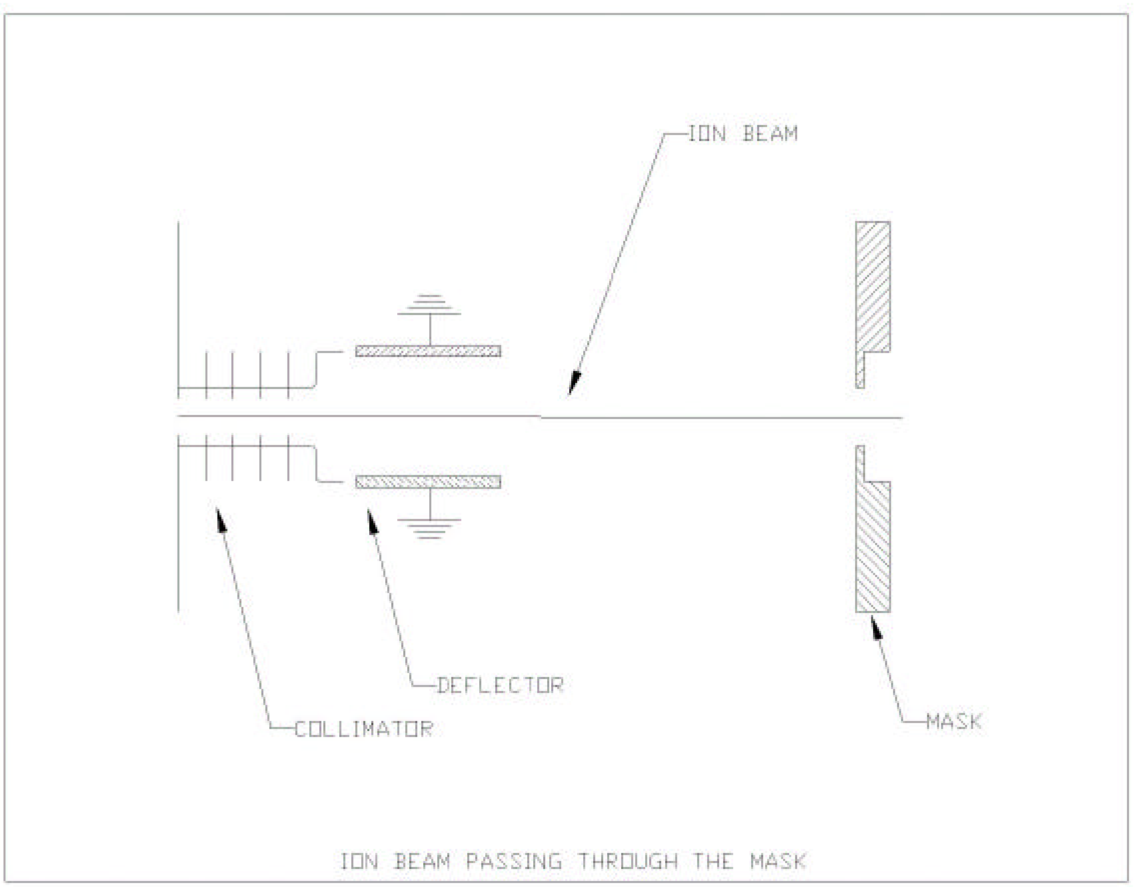

Figure 4 – Ion Beam With No Deflection

When the deflection voltage reaches a certain point the ions will be deflected through the hole in the mask directly below the first hole, as seen in Figure 5.

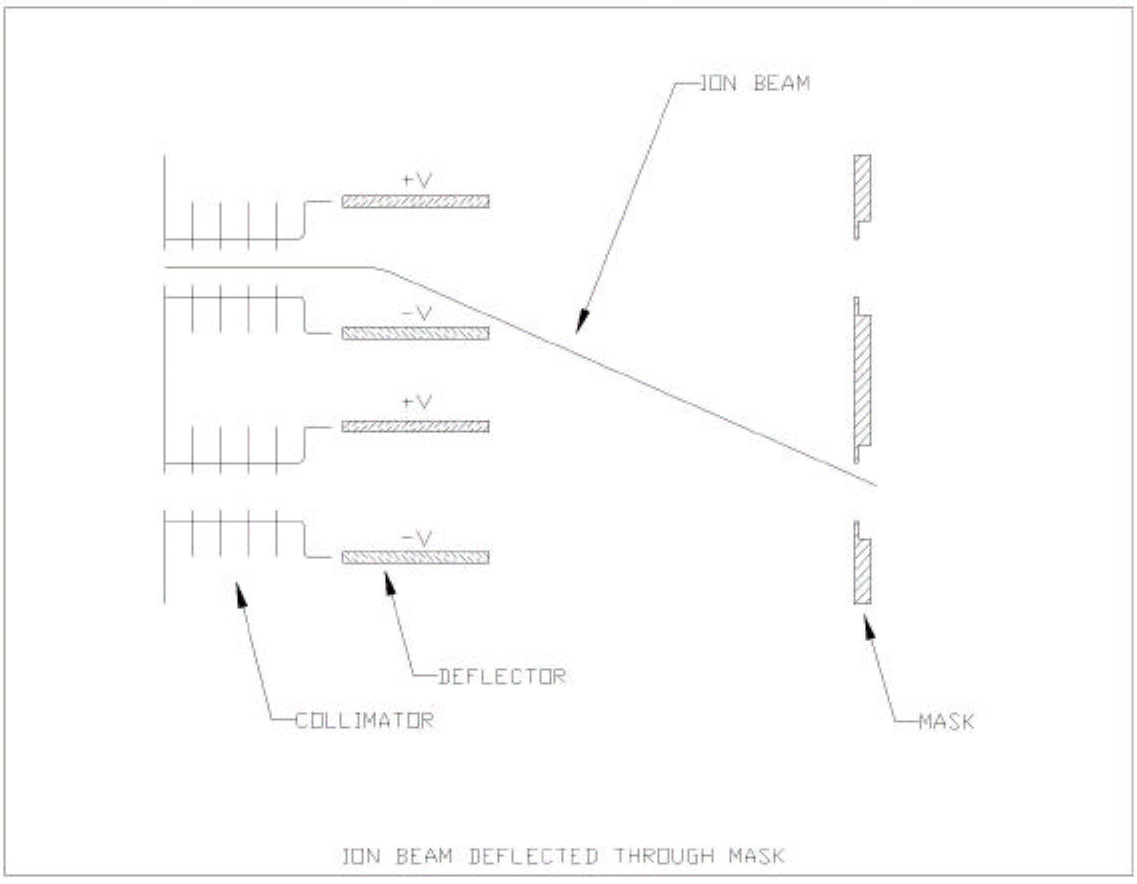

Figure 5 – Ion Beam Deflected Through Secondary Hole in Mask

The vertical distance between the holes in the mask is 800μm, corresponding to the vertical distance between holes in the collimator. Figure 6 provides a detailed view of the mask. It is obvious that the voltage required to displace the ions one slot is proportional to the ion's kinetic energy. It is with this technique that one hopes to determine the ion kinetic energy spectra.

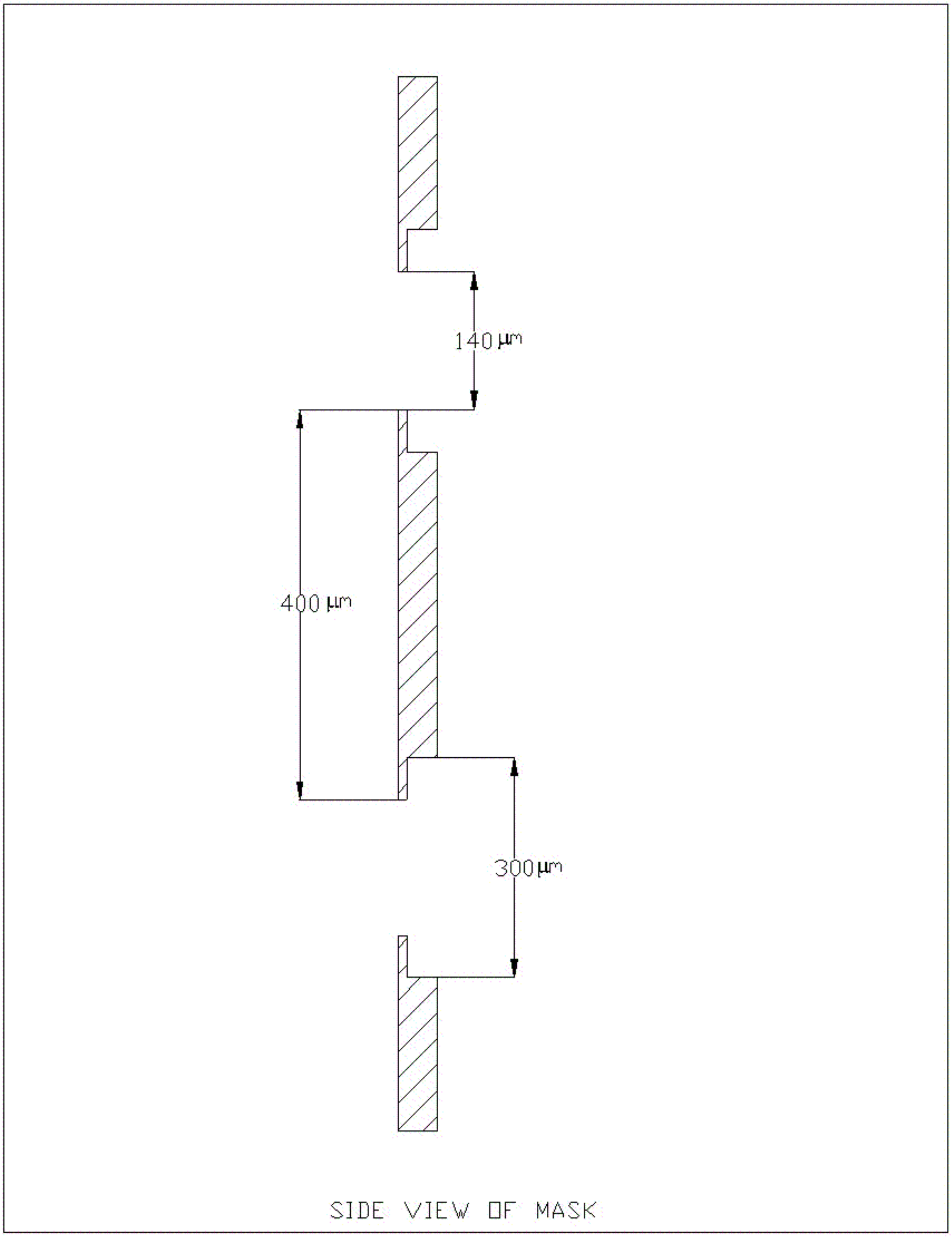

Figure 6 – Detailed View of the Mask

The detector is, at the moment, simply a metallic plate positioned behind the mask.

ION BEAM APPARATUS

The prototype spectrometer is being tested in the ion beam apparatus located in the Atomic Physics Laboratory of the College of William and Mary. The following are certain specifications of the apparatus (Champion, et. al, 8.):

- Ion beam: Either positive or negative, mass analyzed with resolution $m/\Delta m \cong 50$.
- Species available: The ion source is currently a simple discharge source capable of producing most any desired species, with appropriated caveats about intensities for certain species.
- Currents available: Some examples: Ar^+, H_2^+, H_3^+, N_2^+, CF_3^+, … (10nA); O^+, Cl^+, O^-, H^-, ($\cong$1nA); H^+, N^+, … ($\cong$0.2nA).
- Energy range and resolution: The resolution of the ion beam, ΔE, is about 0.5 eV with E ranging from a low of about 10 eV up to almost 1 keV.
- Vacuum in test chamber: Approximately 10^{-7} torr.

- Test chamber: Contains platform with three-dimensional motion and rotation capability. The spectrometer may be attached to this platform. Numerous electronic connections are available within the chamber.

Figure 7 shows a schematic diagram of the ion beam apparatus.

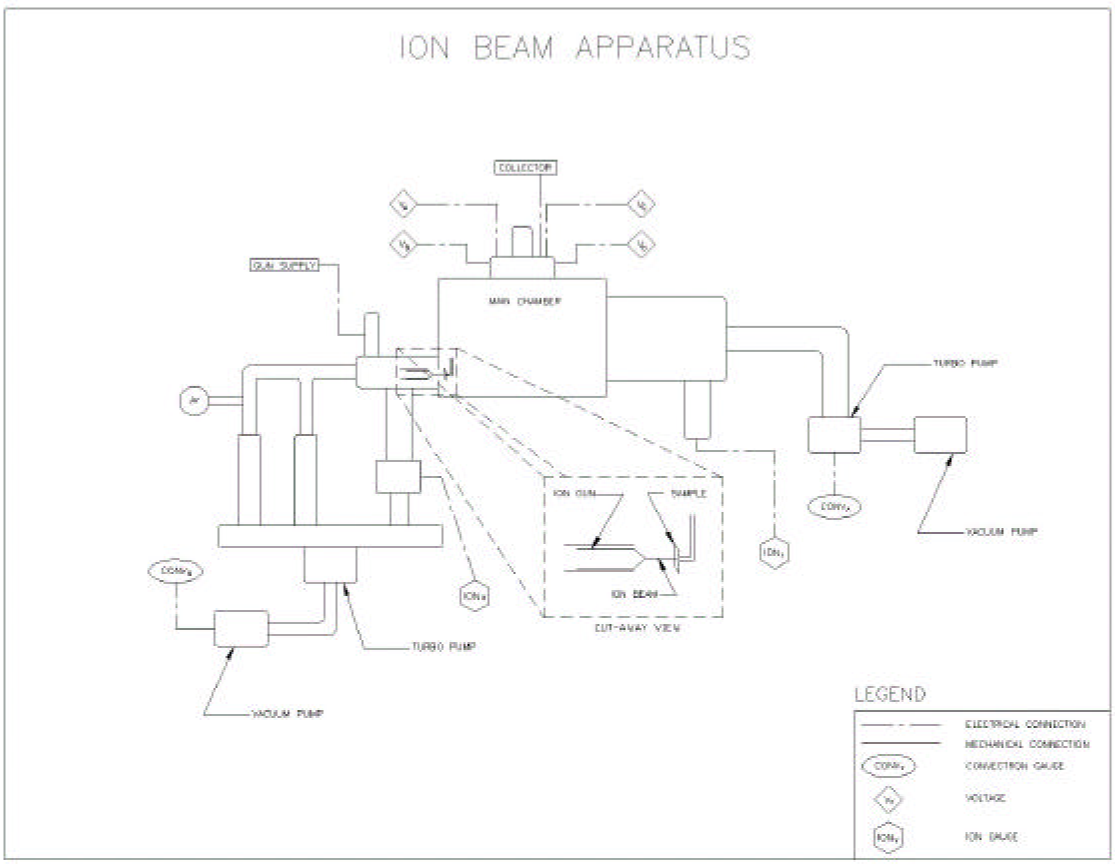

Figure 7 – Ion Beam Apparatus

TRANSPARENCY OF Si WAFERS

In order to ensure that the ion beam would pass through the Si, the transparency of a Si grid was tested. To test the transparency of the specimen, a beam of Ar^+ particles was selected. This particular beam was selected because Ar^+ already existed in the system. The ion beam was maximized by adjusting the voltages of the lenses in the apparatus. A metal plate was mounted behind the Si wafer and initial measurements were made without the Si wafer in place. The beam was focused onto the metal plate and a blank reading of the current on the metal plate was taken. The Si was then set in place, the ion beam was produced, and readings of the current on both the Si wafer and the metal plate were taken. The current present on the metal plate shows how many ions have passed through the Si grid. Dividing this current by the blank current readings taken of the metal plate alone gives the percent transparency of the Si wafer. Higher transparencies show a greater number of ions passing through the silicon wafer. The maximum transparency was approximately 4%, and occurred at voltages between 300 and 400 eV. Figure 8 shows a graph of the transparency of a single silicon wafer.

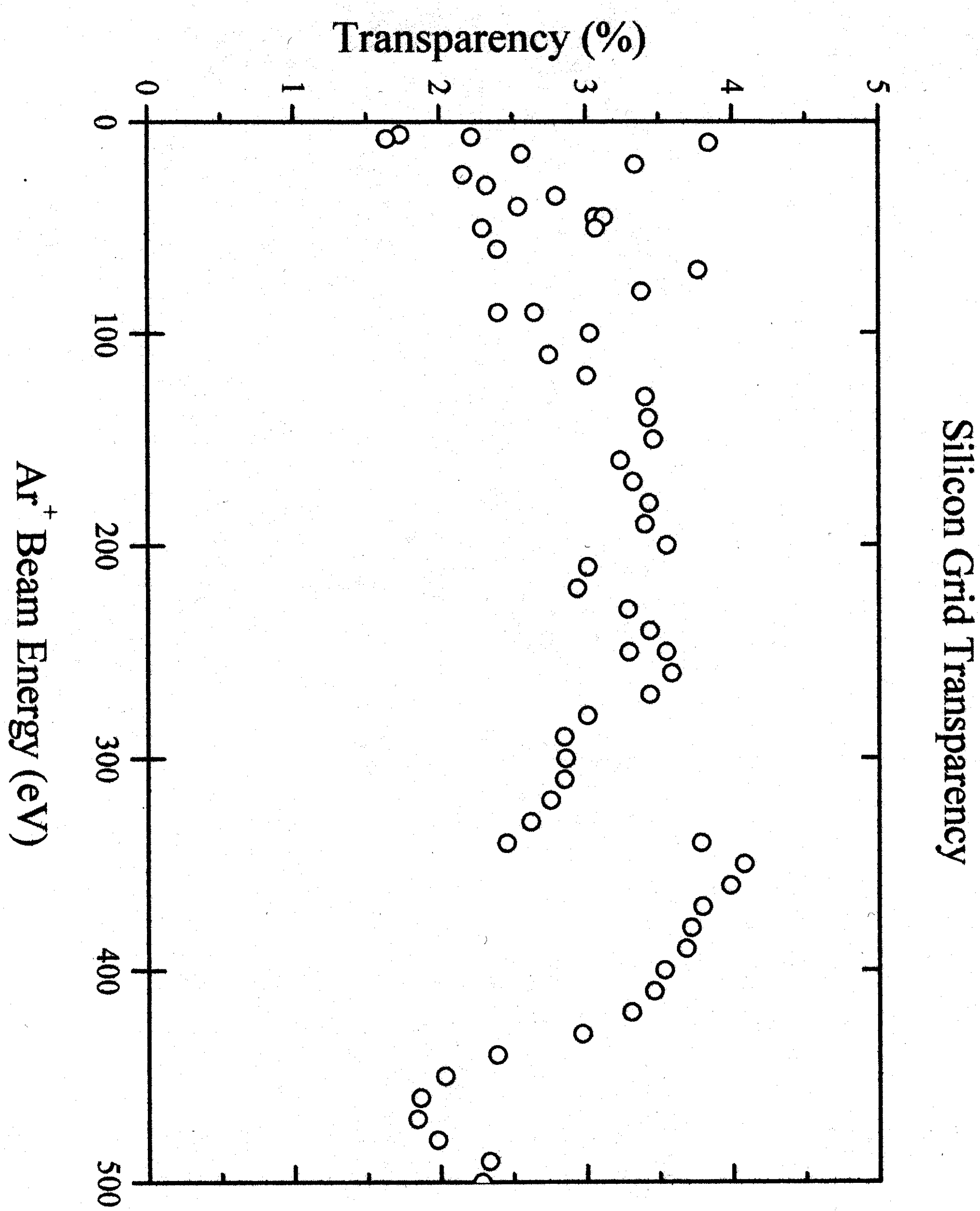

Figure 8 – Transparency of Si Wafer

SYSTEM MODELING USING SIMION

SimIon 7.0 is software that has been developed to show the behavior of ion beams passing through electrodes. Once the geometry of the system is duplicated using SimIon, the software allows the user to define the parameters of the system, such as the energy of the ion beam, the number of ions that compose the beam, and the voltages of the electrodes in the system. SimIon has been developed in such a way that it calculates the electric fields present in the system. In working with the FlaPS system this information was crucial. Normally, electric fields could be calculated mathematically, with no need of computer modeling such as provided by SimIon. The geometry of the FlaPS system, however, makes it difficult to account for fringing fields. An electric field is present between the deflector plates with fringing present at the end of the plates. Normally the effect of such a fringing field would be minimal, but because the distance between the deflector plates is relatively large when compared to their length, these fringing fields must be taken into account. This is easily done using SimIon, as analytic calculations could be quite tedious.

PRELIMINARY TESTS

In the preliminary tests conducted using SimIon the geometry of the FlaPS system was slightly different from that shown in Figure one. The dimensions of the collimator were identical as those in Figure 1, but the deflector plates were only approximately 0.3mm in length, compared to 2mm as shown in figure one. The exact position of the detector in relation to the collimator was not known and estimated to be about 4.2mm from the end of the collimator. Also, in the preliminary model a metallic grid was drawn close to the detector. The purpose of the metallic grid, at ground potential, was to ensure the absence of electric fields that may have, if present, affected the trajectories of the ions.

Once the apparatus was drawn, the voltages of the ion source and collimator were set a 0 V. Voltages of the deflector plates were set at +5 V and –5 V. The voltage of the metallic grid placed in front of the detector was set at 0 V with the voltage of the detector at –2 kV. Three tests were performed under these circumstances: (1) ion energies ranging with the angles of the ions fixed, (2) ion angles ranging at fixed energies, (3) both ion angles and energies ranging. Figures 9 -11 show each of these three tests as seen using SimIon.

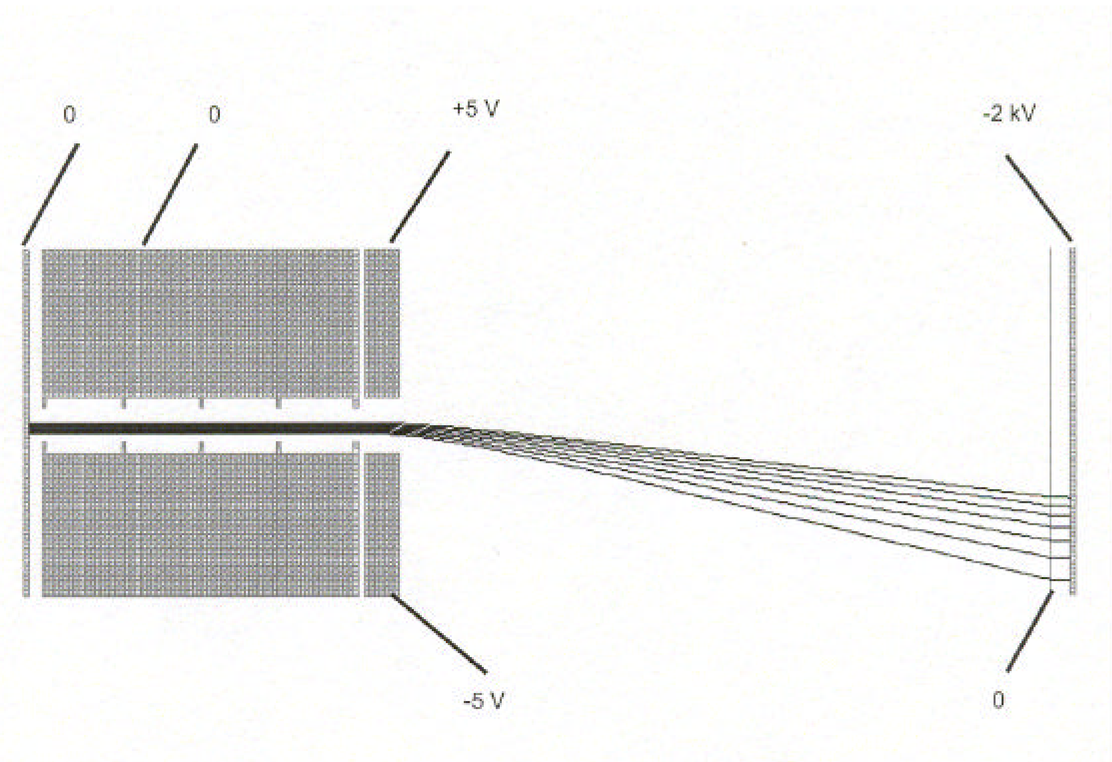

Figure 9 – Change in Kinetic Energy of Ions

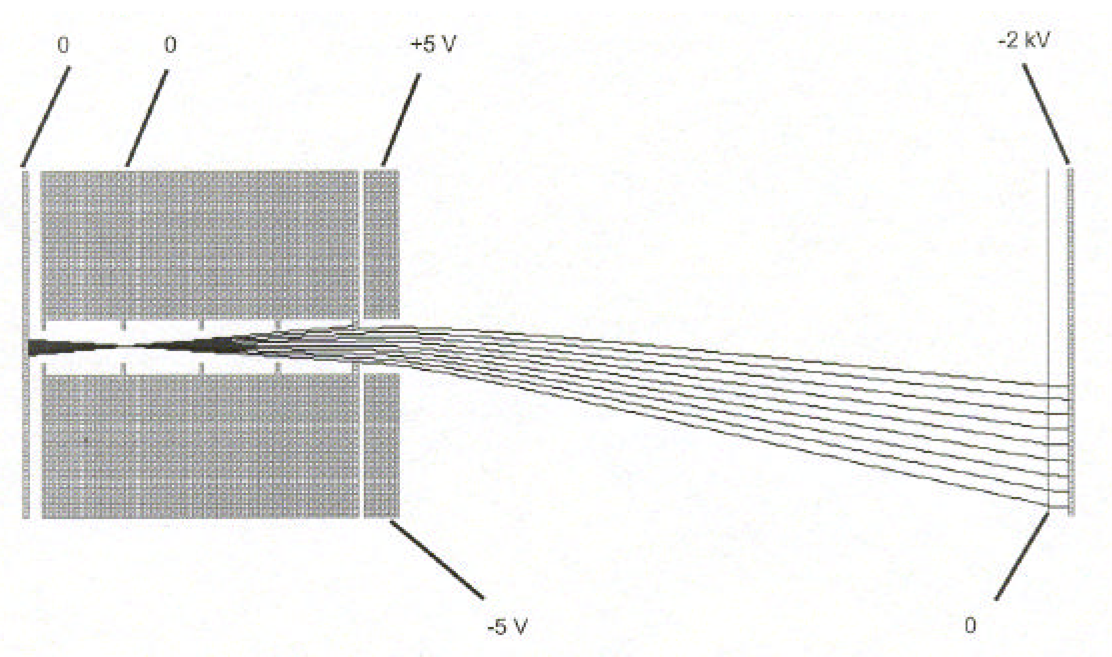

Figure 10 – Change in Initial Angle of Ions

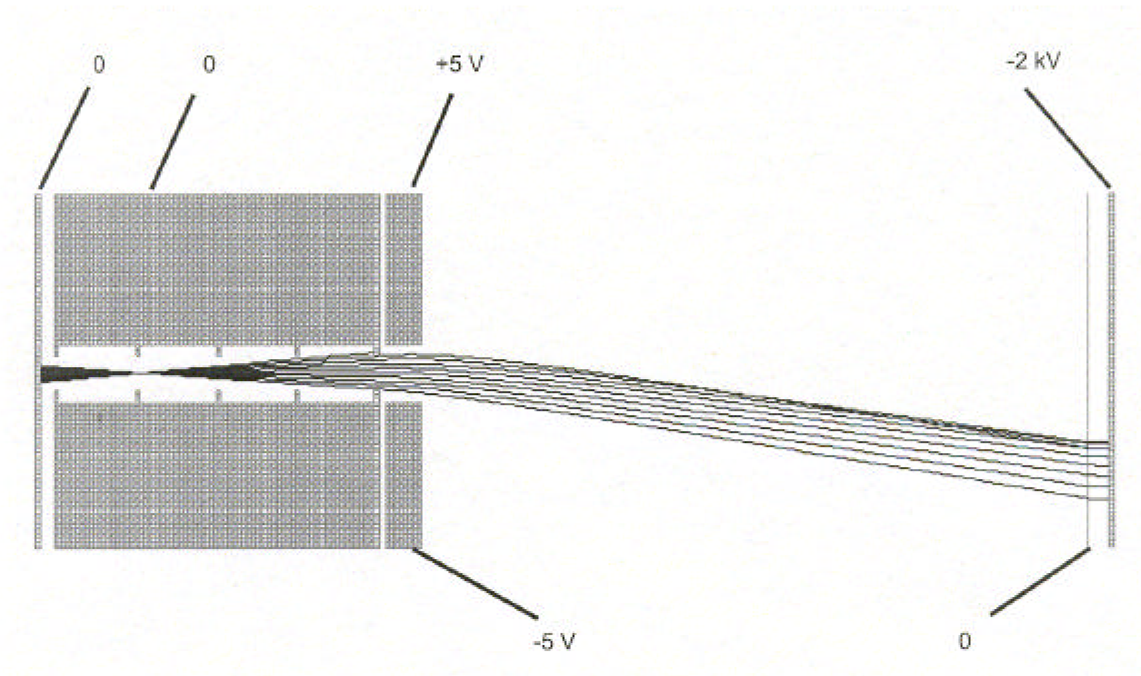

Figure 11 – Change in Kinetic Energy and Angle of Ions

These three tests were performed a second time with the deflector plate voltages at + 8 V and –8 V. Figures 12 - 14 show images of these three tests.

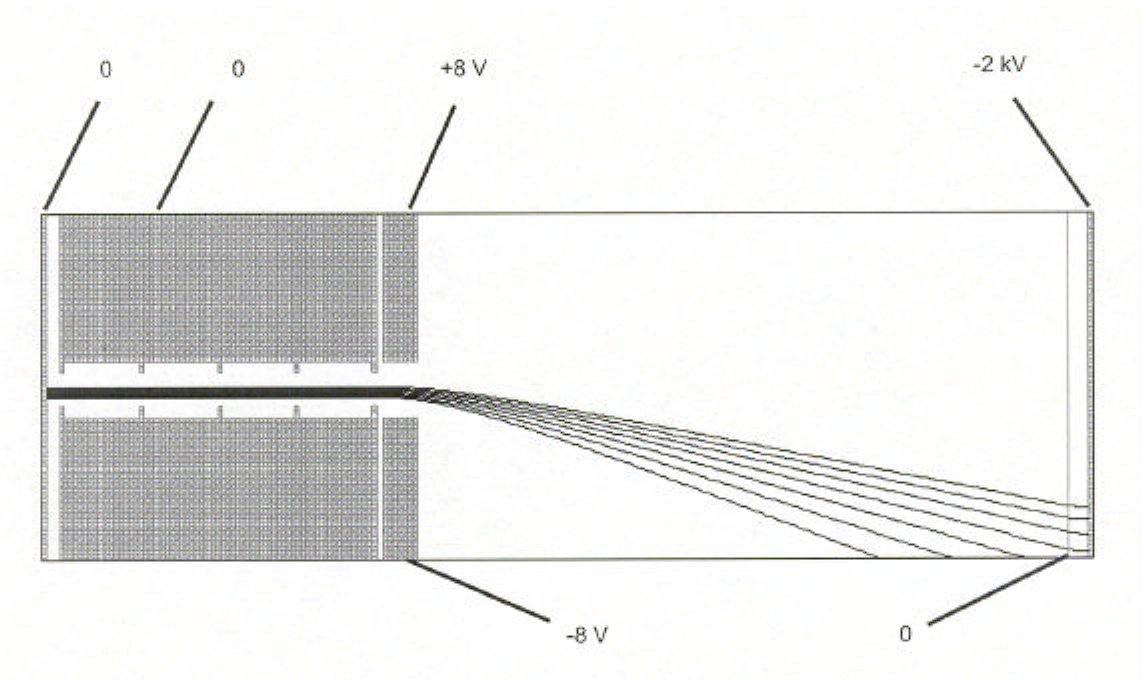

Figure 12 – Change in Kinetic Energy of Ions

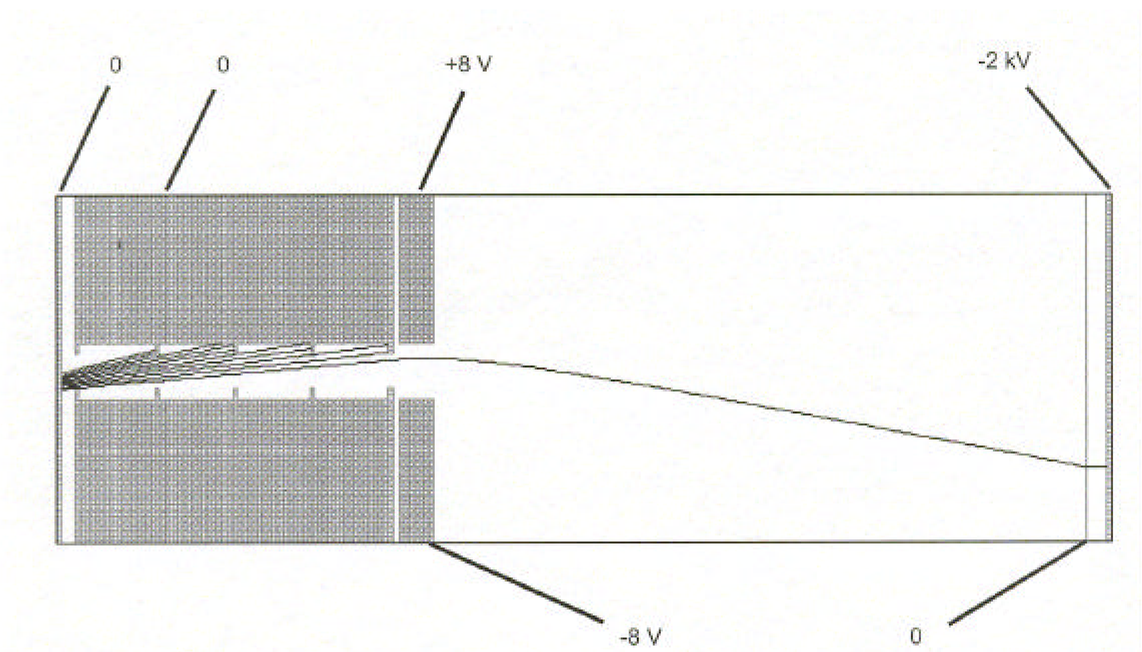

Figure 13 – Change in Initial Angle of Ions

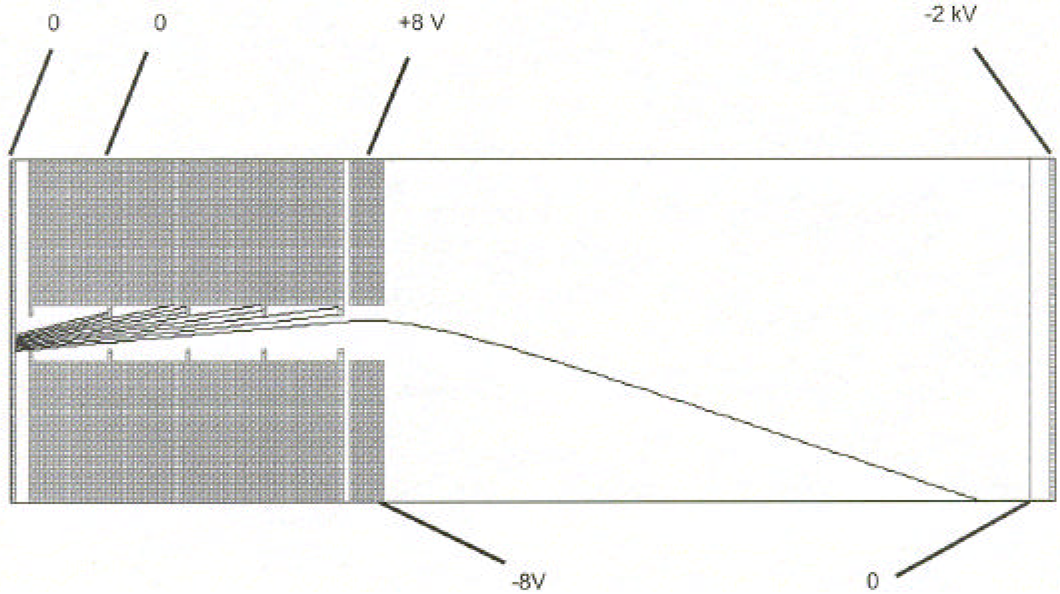

Figure 14 – Change in Kinetic Energy and Angle of Ions

The results of the six simulations illustrated in Figures 9 - 14 give an idea of the ion trajectories of the FlaPS system in the ion beam apparatus.

SECONDARY TESTS

After the preliminary tests using SimIon were completed, the proposed geometry of the FlaPS system changed. The deflector plates were now extended to 2mm, as shown in figure one, and the mask was inserted into the system, with the hole of the mask 800µm below the hole in the collimator. Figure 15 shows this new configuration.

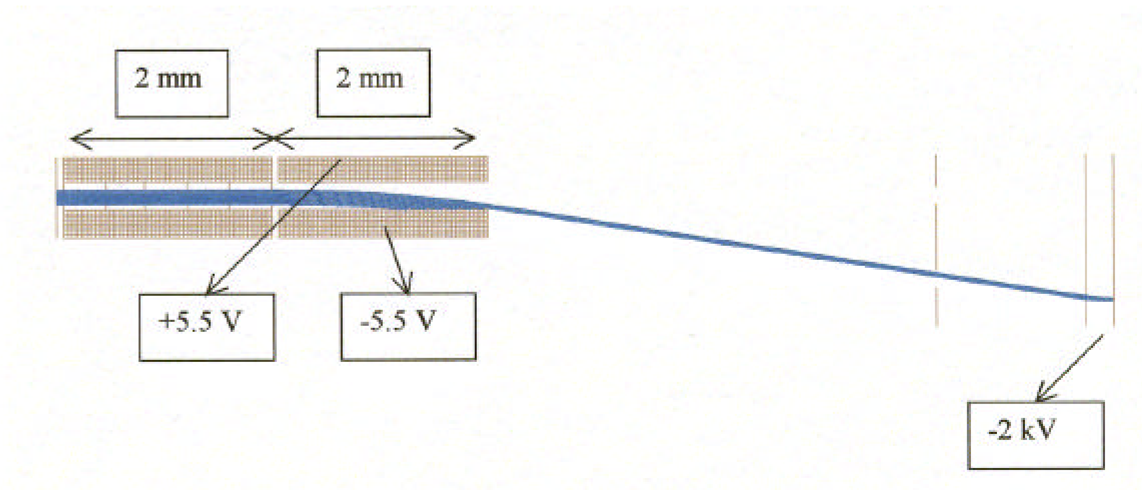

Figure 15 – Change in Kinetic Energy of Ions

In Figure 15 the trajectories of eleven ions are shown but the trajectories of only three ions are undisturbed by the length of the deflector and extend all the way to the mask. This presented a problem. To ensure that the majority of the ion trajectories extended to the mask the deflector plates would need to be shortened. The system was redrawn in SimIon in two new configurations: one with the deflector plates having a length of 1mm, and one with the deflector plates having a length of 0.8mm. Once these configurations were drawn, the parameters of the kinetic energy and the displacement angle theta were changed as in the preliminary tests. Figures 16 - 19 illustrate the ion trajectories under these new circumstances.

Figure 16 shows seven ion trajectories at an original kinetic energy of 300eV and a change of 15eV between ions. Of the seven ions, seven reach the mask and three reach the detector.

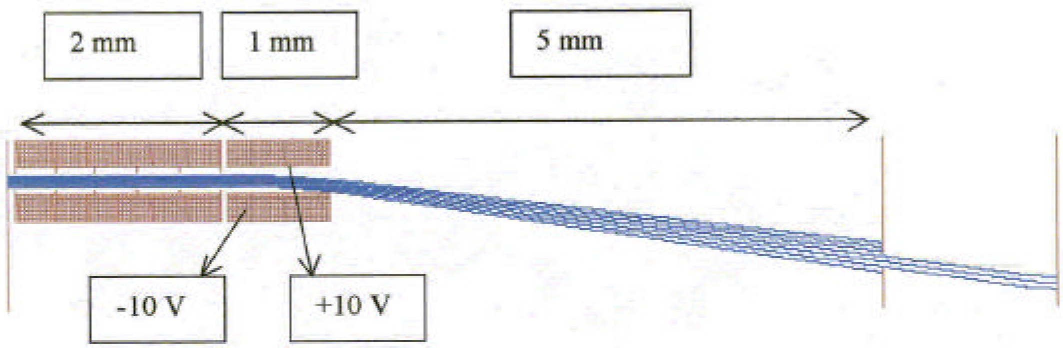

Figure 16 – Deflector Plates at 1mm

The image in Figure 17 has the same dimensions and voltages as the image in Figure 16. In addition to the change of kinetic energy shown in Figure 16, Figure 17 shows a change in angle of 3.5 degrees in steps of 0.5 degrees. Of the seven ions, four reach the mask and only one reaches the detector.

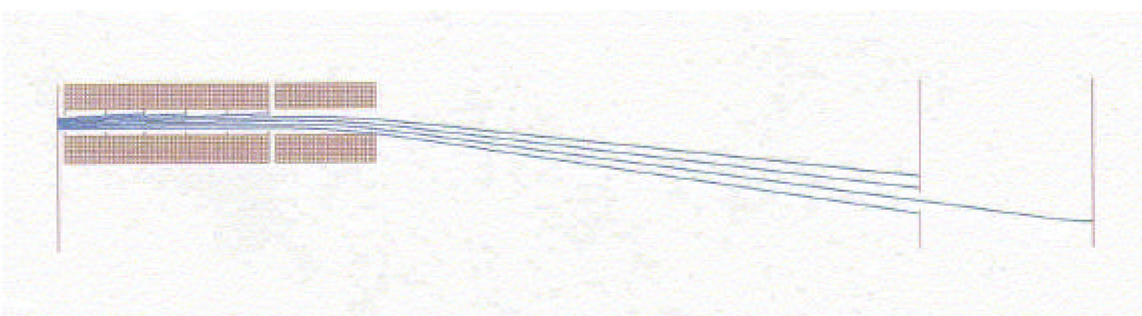

Figure 17 – Change in Kinetic Energy and Angle of Ions

The image in Figure 18 shows seven ion trajectories with an initial kinetic energy of 300eV and a change of 15eV between ions.

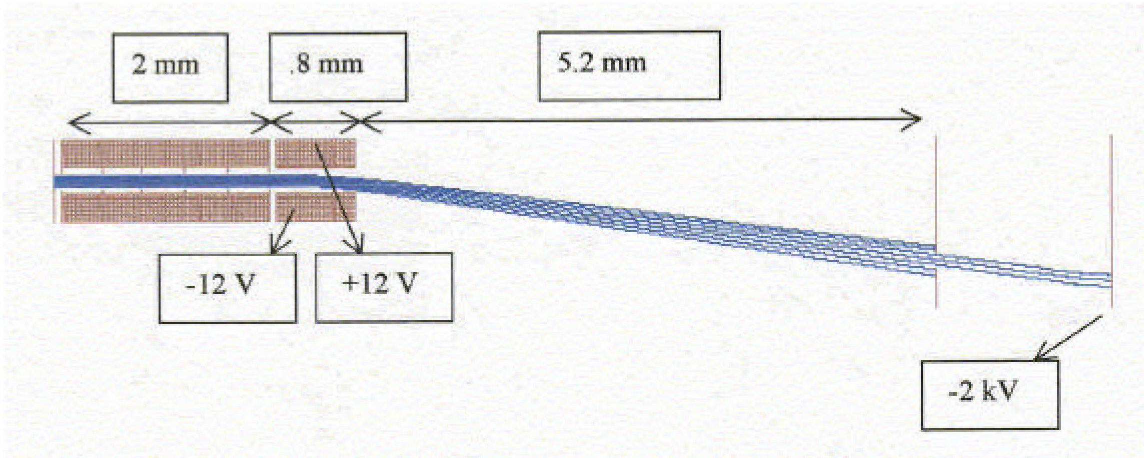

Figure 18 – Deflector Plates at 0.8mm

Figure 19 shows an image with the same dimensions and voltages as the image in Figure 18. In addition to the change in kinetic energy shown in Figure 18, Figure 19 shows a change in angle of 3.5 degrees in steps of 0.5 degrees.

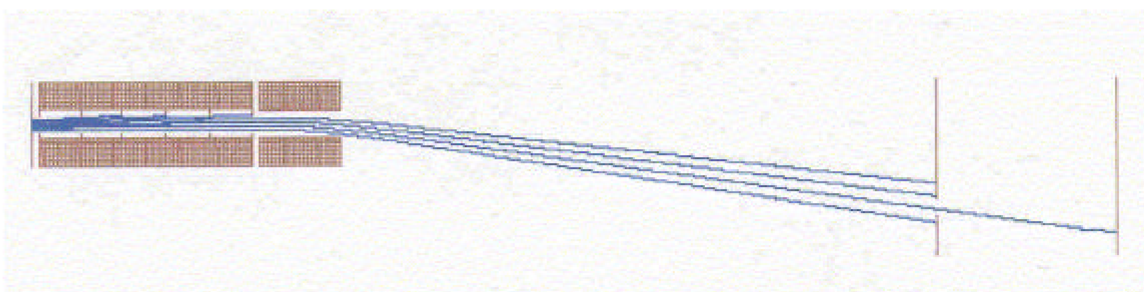

Figure 19 – Change in Kinetic Energy and Angle of Ions

The secondary tests performed using SimIon made it clear that the deflector plates at 2mm were too long to allow for many ion trajectories to pass through them. Images such as those shown in Figures 16-19 were sent to the Johns Hopkins University Applied Physics Laboratory to show the need for shorter deflector plates. The Johns Hopkins University Applied Physics Laboratory was then able to construct new deflector plates with a length of 1mm to allow for more ions to pass through them.

VOLTAGE AND CURRENT TESTS

The next step in the project involved performing tests on the device as depicted in Figure 1. Voltages were assigned to the deflector plates and the rest of the apparatus was held at ground potential. Ions were projected through the collimator, deflector plates, and mask, and the current of the ion beam was read on the collector. Initial tests were performed to assure that the ion beam would hit the mask. After these initial tests were conducted, subsequent tests were conducted by varying the voltage on the deflector plates while monitoring the amount of current being read on the collector. The results of these tests are illustrated in Figure 20.

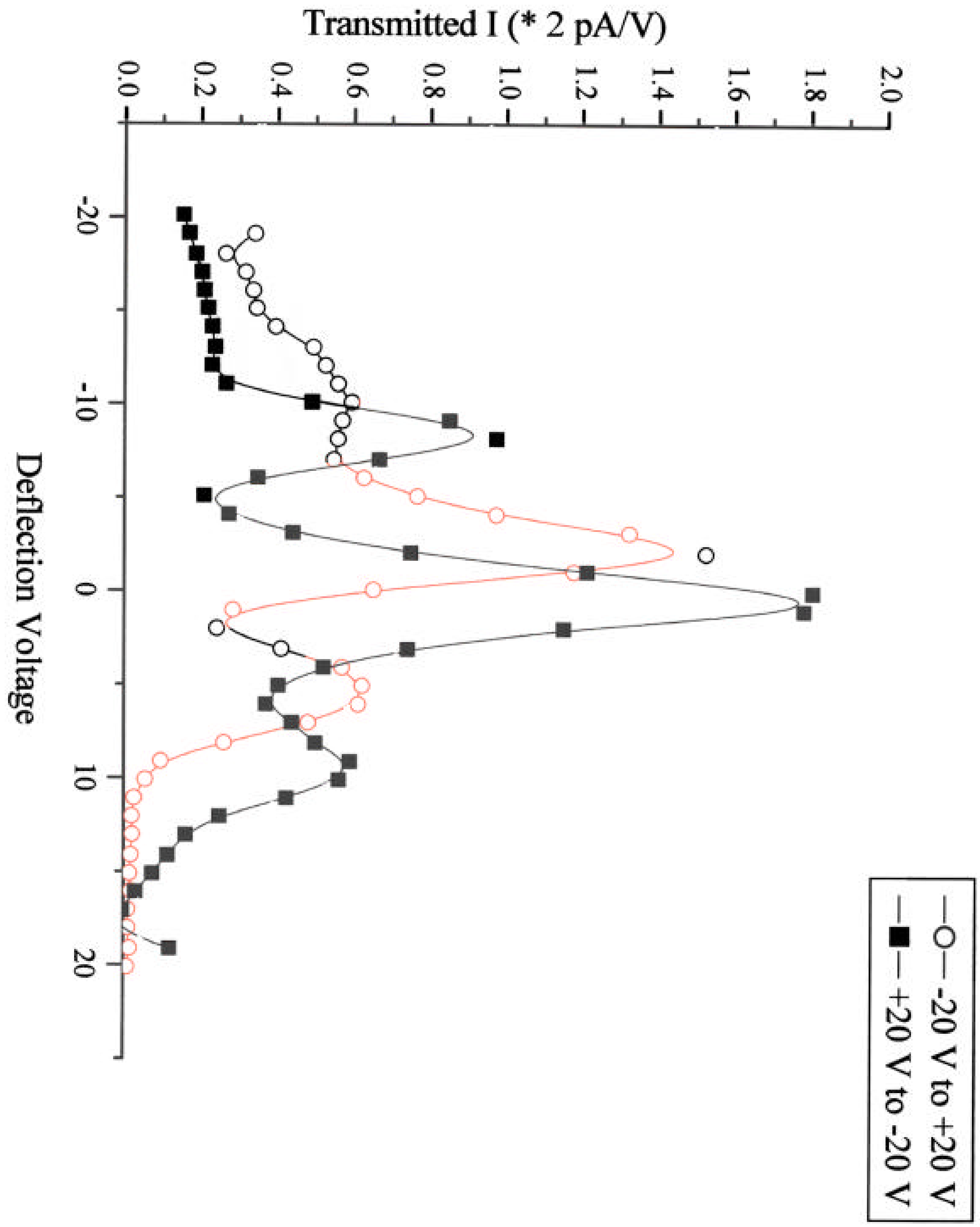

Figure 20 – Deflection Voltage and Transmitted Current

This graph exhibits unexpected behavior. The graph shows an evident hysteresis between –20 and 0 volts on the gray graph and 0 and +20 volts on the black graph. The hysteresis indicates that some element of the FlaPS system is charging up. On the graph of the second set of tests conducted, the hysteresis is also present. This graph is shown in Figure 21.

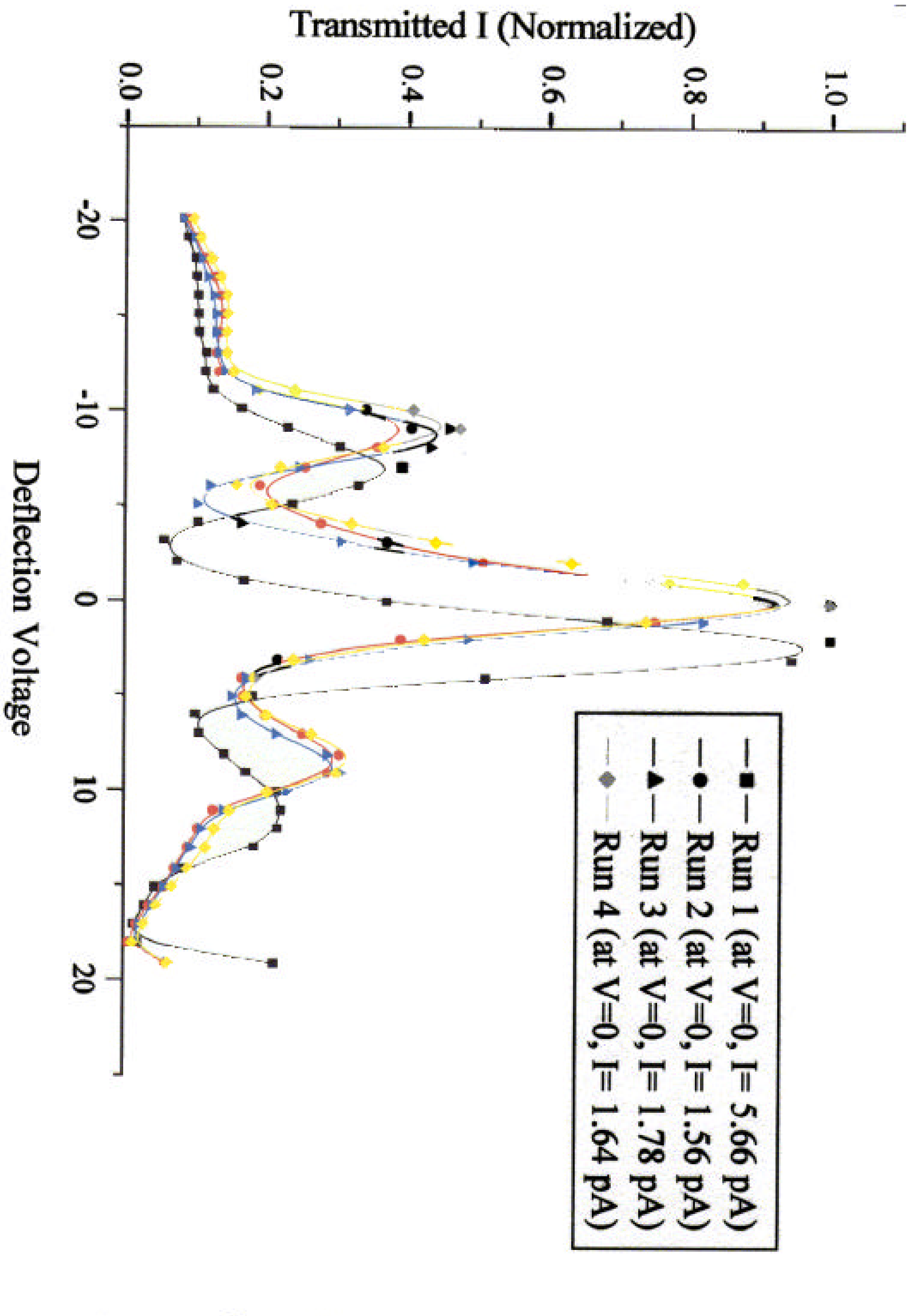

Figure 21 – Deflection Voltage and Transmitted Current

This graph gives information for four different initial ion beam currents. The hysteresis is present again in this graph for each of the four tests. The voltage on the deflector plate is raised and then returned to zero. As the voltages are set back to zero, the point at which the maximum occurs has changed. This indicates that some part of the FlaPS system that was not assigned a voltage has charged up during the testing. A short of 4MΩ was found between the deflector plate and the collimator showing that the collimator is not totally insulated, as it should be, from the deflector plate.

CONCLUSION

The next step in the development of the FlaPS is to address the problem of charge accumulation as seen in the tests shown in Figures 20 - 21. There are two possible sources of this effect. The first possible source is the insulators. It is possible that the ions projected through the apparatus could “see” the insulators, in other words, that the insulators were not totally insulated form the system. If the ions could “see” the insulators, the insulators could become charged. The second possible source of the excess charge could be the ohmic contacts between the collimator and the deflector plates. The original ohmic contact between the collimator and deflector plates was on the order of several MΩ. To prevent current from flowing from the deflector plate through the collimator an ohmic contact on the order of 10^{12} Ω is desirable. The Johns Hopkins University Applied Physics

Laboratory, which fabricated the prototype FlaPS system, is currently addressing the possibilities of charge accumulating by one of these two processes. Adjustments in the model will be made according to their findings and testing of the system will then resume at the Atomic Physics Laboratory of the College of William and Mary.

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