Building an Ion Chamber to Perform Beam Profile Measurements

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The 76-inch cyclotron at Crocker Nuclear Laboratory (CNL) requires measurements of the beam current to calculate the amount of radiation dose an object will receive when placed in front of the beam. We built an ion chamber that will provide localized real-time measurements of the beam profile. These measurements that characterize the beam profile will then be used to characterize the transverse variations in dose. When changing the energy of the beam, the profile can also fluctuate. The ion chamber allows for these slight changes to be taken into account by immediately recalculating new values to be used in dose calculations. Those new values are scaling factors used to determine the position dependent flux based on the total beam current.

Introduction

The Crocker Nuclear Laboratory is equipped with a 76-inch cyclotron [2]. The cyclotron can accelerate many particle species including protons, deuterons, alphas, neutrons, and helions. The proton beam which was used to test the ion chamber, can be tuned up to 67.5 MeV [3]. When the desired charged particles enter the center of the cyclotron, magnetic fields apply a force that causes the particles to travel in a circular path. Whenever the particles cross the center gap of the cyclotron, they are accelerated by an electric field. Since the cyclotron is isochronous, a magnetic field increases radially to keep the period of the particles constant as their energy increases. This allows the particles to be continuously accelerated by a voltage that alternates at a constant frequency. Once the particles reach the desired energy they are then directed out of the cyclotron and down one of the beam lines shown in figure 1.

One of the main uses of the cyclotron at CNL is commercial testing of radiation effects, which is done in beam line 2. The cyclotron is also used to treat ocular cancer every month. The ion chamber we built works similarly to the profile monitors used in the Eye Therapy Facility [5]. Typically, the shape of the beam, or the beam intensity profile is measured using Gafchromic film [4], which is a radiotherapy film that changes color when exposed to radiation. Figure 2 shows an example of the spatial distribution of the beam. It is important to collect information about the intensity and shape of the beam in order to accurately understand how the radiation affects the objects that are exposed to the beam. In addition to the Gafchromic film, the ion chamber is another method of collecting these measurements. Figure 3 illustrates how the chamber functions. When a bias voltage is applied across the aluminum foils that are located at each end of the cylindrical chamber, an electric field is created. As the proton beam passes through this field, the electrons are swept through to the positive side while the positive ions are swept in the opposite direction. The movement of these particles creates a current that the circuit in the center of the ion chamber can read out.

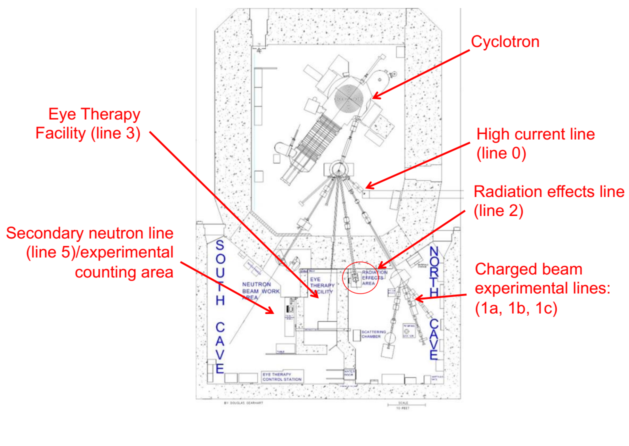

FIG. 1: Crocker Nuclear Lab layout

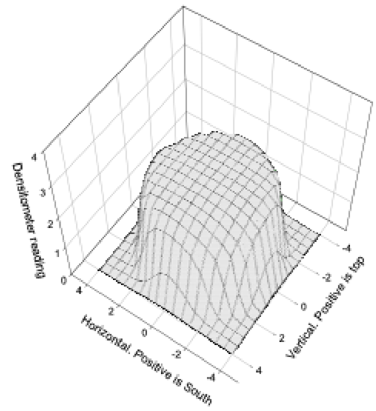

FIG. 2: Spatial distribution of the beam

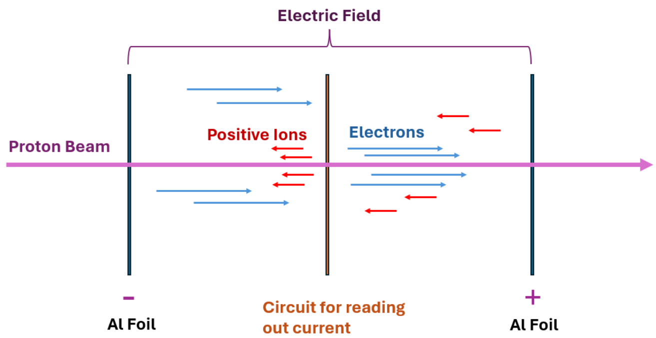

FIG. 3: Diagram showing ionization in chamber

Either Gafchromic film or an ion chamber based profile monitor can be used to calculate what are known as scaling factors by converting total beam current to a localized flux. These scaling factors are an important part of dose calculations. The dose calculations provide information about how an object has been affected by the beam, the scaling factor is what allows us to specify how a certain area has been affected by the beam. Some of the commercial tests involve varying aspects of the beam such as the beam energy. However, these calculations are done under the assumption that the beam profile stays constant. In some cases, the slight changes in the beam profile have affected the quality of the results when the beam energy is varied between runs. This is where the ion chamber becomes an improved method since it takes much less time to extract the correct numbers. As a result, in addition to providing a better understanding of beam calibration, the ion chamber will also recalculate the scaling factors in real time to account for any minor differences.

Simulations

Before building the ion chamber, simulations were used to optimize the design. G4Beamline [6], a Monte Carlo simulation and a wrapper for Geant4 [7], was used to model the effect of the electric field in the ion chamber. The chamber model consists of a circular sheet of Kapton 0.127 mm thick and 18 cm in inner diameter, which is then adhered to a circular sheet of aluminum foil 6.35 μm thick and 18 cm in diameter, after there is a 2.5 cm gap of air followed by 4 aluminum pads 12 μm thick and each 12 mm in diameter. These pads were placed in a vertical line from the center of the chamber. The chamber is symmetrical and therefore followed by another air gap, sheet of aluminum foil, and lastly Kapton, all with the same dimensions. The inner diameter of the chamber was then varied in the simulation to locate the ideal dimensions where the electron count across the pads was uniform; with the goal of avoiding possible edge effects from the electric field. The data shows that the optimized inner diameter of the chamber is 18 cm.

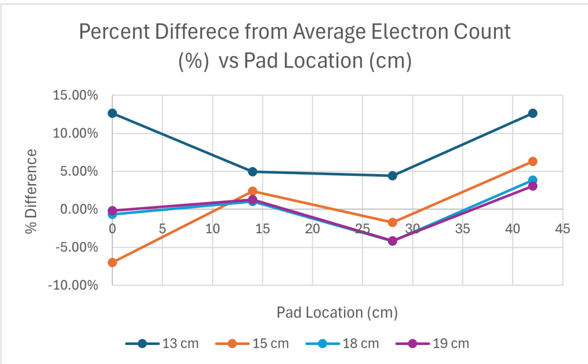

FIG. 4: Electron count variation across 4 pads for 2 million runs

This result can also be seen in Figure 4 and Figure 5 where the 18 cm diameter resulted in the lowest percent difference

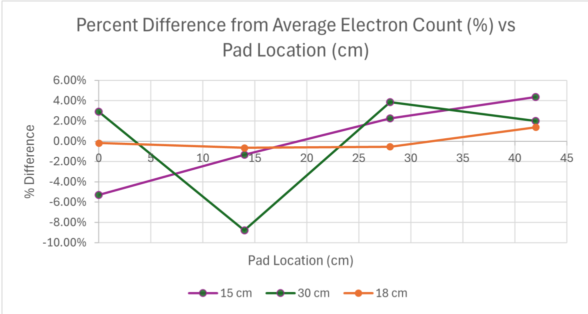

FIG. 5: Electron count variation across 4 pads for 8 million runs

across the pads from the average electron count.

Building the Ion Chamber

When building the ion chamber, the goal was to make the first version as cost efficient, simple, and quick as possible. The frame of the ion chamber was modeled in OpenSCAD and 3D printed in 4 separate pieces (Figure 6).

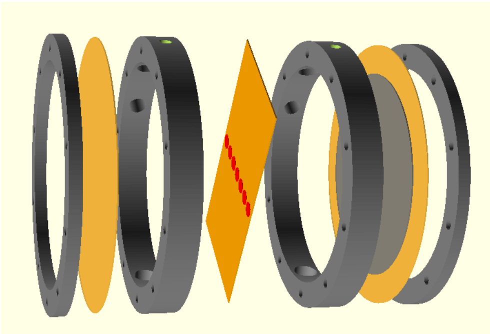

FIG. 6: Simplified diagram of ion chamber

We then cut circular pieces out of Kapton and punched holes for the screws that hold the chamber together. The thin aluminum foil was carefully cut out with an exacto knife and glued to the Kapton. Each of the two pieces also had holes to connect wires to for applying a bias voltage across the aluminum foil. Separate wires were then soldered to 7 BNC connectors and to the edge of the circuit which is placed in the center of the chamber. The circuit was designed in electronic design software (KiCad), and then printed through a PCB board printing company (Figure 7).

The circuit itself is 26 by 10 cm with a total thickness of approximately 0.07 mm. The 2 layer board consists of a copper layer of 7 copper pads placed in a vertical line along the center of the circuit and then copper tracks to soldering connectors, this copper layer is electro-deposited on a 25 μm polyimide layer. Lastly, a masking layer was added to prevent any possible interference from the copper tracks. The edge of the circuit was also designed with a length that allows the connectors to be slightly outside of the chamber's frame, so that the wiring will also stay outside of the chamber. A sheet of

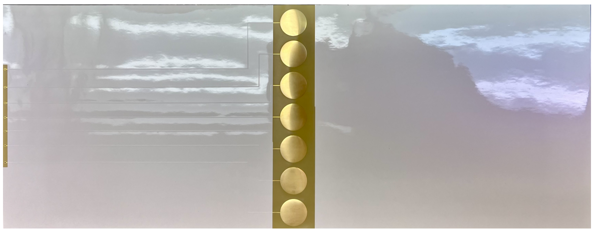

FIG. 7: Front of the circuit designed to collect data from the chamber. The column of exposed copper electrodes in the center are what measure the current when exposed to the proton beam.

metal was then cut and shaped to create a box attached to the outer frame of the chamber to contain the wiring and 7 BNC connectors to read out the data. These were then connected to 7 Keithley ammeters to read out the current during beam tests. A stand was also designed and printed using a resin printer to securely attach the ion chamber to the optical table in front of the cyclotron beam line. Two smaller rectangular pieces were also resin printed so that the section of the flexible circuit outside of the frame could be placed between to ensure stability and protect the soldering connections due to their small scale.

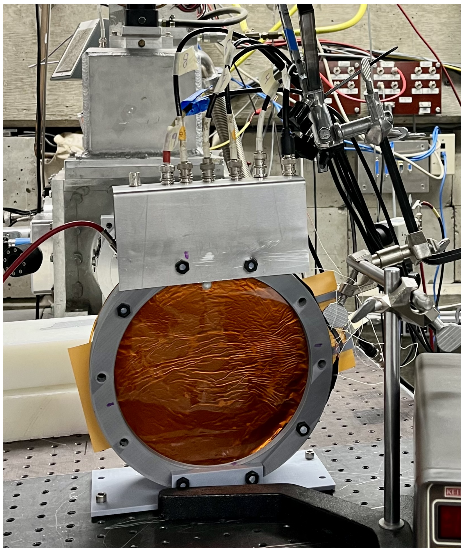

FIG. 8: Ion chamber setup in front of beam line

Beam Profile Results

The cyclotron proton beam profile was measured by applying a bias voltage of 1400 volts to the ion chamber and then exposing it to a proton beam from the cyclotron. The results showed that the method of using a GPIB bus communicator to receive data from the ammeters through a python program was not sufficient (Figure 9). Since the GPIB bus only allowed for sending and receiving signals from the 7 ammeters used in sequence rather than in parallel, the shortest time interval achieved for recording one data point from each ammeter was 9 seconds. Any shorter and there was too high of a probability that the data wouldn't be received properly. The time delay affects the plots of the beam profile because the cyclotron beam varies in intensity since the machine requires continuous tuning by the operators. However, when manually taking images of the ammeters at one instance in time (Figure 10), the much faster sample rate due to the camera reduced the error. As a result, the beam profile plotted from this data was more accurate and produced a much smoother curve. To fix this issue in the future, electrometers with more than one or two channels could be used instead for quicker data collection.

FIG. 9: Average beam profile recorded with python script

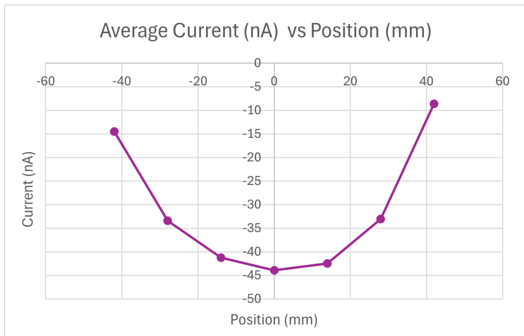

FIG. 10: Average beam profile from manually recorded data

Scaling Factor Calculations

The ion chamber measures the flux of the beam, which means it measures how many protons pass through a certain area over time. The flux can then be used to calculate a scaling factor which is used to calculate the amount of dose something receives based on its area when it is exposed to the beam from the cyclotron (Equation 1). The flux of each individual copper pad is calculated by dividing the current reading (which is multiplied by the number of electrons in one Coulomb (6.24×10^{18} electrons)) from the pad by it's area (layout shown in Figure 11), and then scaling it to an area of 1 cm squared (Equations 2-3). Some of these scaled flux values are then averaged to increase the accuracy of the calculations, since most of the ion chamber area sections contain two pads.

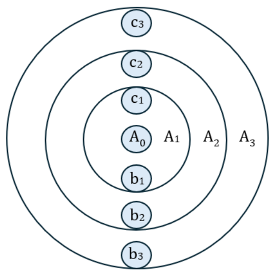

FIG. 11: Diagram of copper pad layout in ion chamber

$$\phi_{pad} = \frac{I(6.241 \times 10^{18} electrons)}{A} \tag{1}$$

$$\frac{I_{pad}}{A_{pad}} = \frac{I_{scaled}}{1cm^2} \tag{2}$$

$$I_{scaled} = \frac{1cm^2}{\pi r_{pad}^2}(I_{pad}) \tag{3}$$

Now we can assume that all four of these flux values represent the flux of each of the four area sections. The current of each section is calculated by multiplying these fluxes by its respective area (Equations 4-6).

$$I_{A_0} = (\phi_{A_0})(A_0) \tag{4}$$

$$I_{A_0} = (\phi_{A_0})(A_1 - A_0) \tag{5}$$

$$\vdots$$

$$I_{A_3} = (\phi_{A_0})(A_3 - A_2 - A_1 - A_0) \tag{6}$$

The total current in the ion chamber is calculated by adding together each of the four currents (Equation 7).

$$I_{ionchamber} = \sum_{n=1}^{3} I_{A_n} \tag{7}$$

Lastly, the scaling factors can now be calculated by dividing the flux of a desired area by the total current in the ion chamber (Equation 8). The total area is only left out because the area from the flux in the numerator is a necessary part of the fluence calculations. The scaling factors can now be used to calculate both the fluence and the dose that something of a particular area receives when placed in front of a beam.

$$ScaleFactor = \frac{\phi_A}{I_{ionchamber}} \tag{8}$$

Equation 9 shows how the scaling factor allows for the local flux to be calculated since the current measured in the beam line is known.

$$\phi_{local} = I_{beamline} \times ScaleFactor \tag{9}$$

Scaling Factor Results

Using the calculations previously described, the following scaling factors were calculated (Table I)(Figure 12).

Position (cm)	Scale Factors Currently Used $(\frac{1}{cm^2})$	Measured Scale Factors $(\frac{1}{cm^2})$	Percent Difference (%)
0.0-0.5	0.0200	0.0239	17.8
0.5-1.5	0.0199	0.0233	15.7
1.5-2.5	0.0195	0.0209	6.9

TABLE I: Scale factors for the different areas currently used in BeamMon software [1] compared to the scale factors calculated with the ion chamber.

The values calculated from the ion chamber measurements allow for a better understanding of the calibration of the beam. They also show that the ion chamber can be used to quickly adjust for possible variations in the beam profile when the energy of the beam is changed.

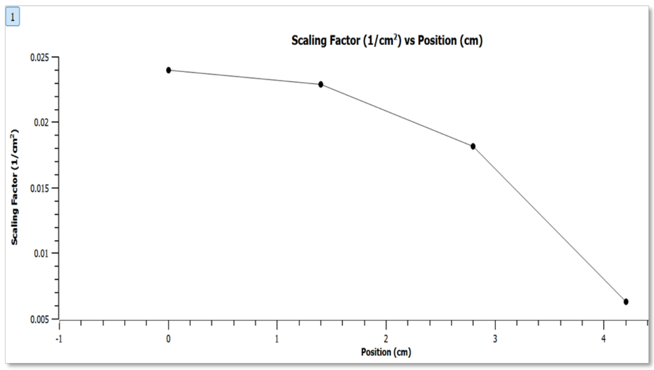

FIG. 12: Scaling factors for varying positions calculated using measurements from ion chamber

Conclusion

The design of this ion chamber was optimized to amplify the signal it reads out with an 18 cm inner diameter. Overall, the chamber allows for a better understanding of beam calibration. When varying the energy of the beam, the ion chamber is also a valuable tool for providing quick corrections to the scaling factors used in dose calculations. This is the first version of the chamber and now that it has been shown to provide these results, the design can be further refined to allow for more precise calculations.

Future Improvements

In the future, the results from the ion chamber can be improved through various possible adjustments. The gas used inside the ion chamber can be changed from air to Nitrogen or Argon which could increase the amplification of the signal. The accuracy of the calculations could also be improved by decreasing the size of the copper pads and increasing the number of electrodes. Ultimately, measurement devices permitting, the design of the circuit could resemble a grid of pixels that each read out the current. In future circuit designs, the connectors will also be adjusted to make connecting wires to the circuit easier and less fragile. Lastly, when the optimal data recording configuration is finalized, a program will be written to calculate the scaling factors while the beam is passing through the ion chamber.

Acknowledgements

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