

Secondary Emission Chamber Calibration

Version 1.0

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Abstract

We report on a study of the behavior of a secondary emission chamber (SEC) when placed in a beam of high energy charged particles. We show the dependence of the SEC signal on the charge and velocity of the primary beam particles when using protons, and Iron ions. We calibrate the response of the SEC to ions by first using a plastic scintillator to count particles traversing the SEC, and transfer the calibration to an ion chamber that can operate at a high enough rate to characterize the SEC. The calibration is determined for the two different ion species and two different energies.

Introduction

This note describes the process of calibrating a Secondary Emission Chamber (SEC) for use as a monitor of high intensity charged particle beams. The response of the SEC to different ion species at several energies is measured, to judge the range of validity of the calibration. We study the operating conditions for which the calibration is maintained.

The Secondary Emission Chamber is a device for measuring the flux of a charged particle beam at high intensities. In order to operate as a beam current monitor, or dose monitor, we need to know the ionization collected when a charged track deposits energy in the SEC. Ultimately we will connect the response of the SEC to a minimum ionizing proton (MIP), measuring the number of electrons produced per MIP. We will compare the SEC response to various ion species at energies, testing whether the calibration scales with deposited energy.

The calibration of the SEC is a two-step process. First, at low beam intensity, the number of ions in the beam is counted using a plastic scintillator and photomultiplier tube (PMT). Simultaneously the ionization produced when the beam passes through a gas volume in an ion chamber is collected and measured. This allows the ion chamber to be calibrated based on the measured particle flux through the scintillator. For the second step, the beam intensity is increased to a level that the SEC can register, and the calibration is transferred from the ion chamber to the SEC.

For this calibration procedure, the SEC was placed in the NSRL facility to study its response to a variety of heavy ion beams under different beam conditions, comparing iron and proton beams. We also studied the response of the SEC to beams of different energies, intensities, and sizes.

Description of the SEC

A complete description of this SEC has been published elsewhere [1]. The SEC is essentially a vacuum chamber with a series of thin silver-coated aluminum foils in the path of the beam. When charged particles traverse the vacuum chamber, they pass through the thin conducting foils, alternating anode and cathode. Ionization produced in the cathode foils travels across the intervening vacuum gap due to an applied high voltage. The electrons are collected on the anode foils and read out with a recycling integrator.

The aluminum foils are 6.35 μm (0.00025") thick with vacuum deposited silver coating that is 0.020 μm thick to improve conductivity. Each foil is held captive between two stainless steel flanges that are 10 cm in diameter. The foils have been baked under vacuum to out-gas the surfaces, and then cleaned with an Argon glow discharge. The foils are separated from each other by a 1 cm gap. The set of five foils are centered in the vacuum vessel, with a 5 cm gap from the 0.5 mm (0.020") thick aluminum vacuum windows to the foils at each end. Figure 1 shows a schematic of the SEC with an entrance and exit vacuum flange, thin vacuum windows and five foils, alternating cathode and anode.

The vacuum vessel is pumped out with an ion pump to 1×10^{-8} torr and the vessel is sealed. Continuous monitoring of the internal pressure shows there are no significant vacuum leaks or outgassing. At this level of vacuum, ionization from residual gas is negligible compared to the ionization released from the foils when traversed by a charged particle. Electron capture is very inefficient in the SEC because most of the ionization in the foils remains trapped within the foil due to the short range of most delta rays. It is this inefficiency that allows the SEC to operate at high dose rates and short pulse duration where standard ion chambers cannot function reliably.

The readout of the SEC is accomplished with a Recycling Integrator (RI) described elsewhere [2]. The RI system provides a virtual ground for the anode, requiring negative high voltage on the cathode foils. It is a charge balance converter, also known as a current-to-frequency converter. Electrons from the SEC are collected at the input until the voltage on the input capacitor triggers a comparator which fires a balancing current source for a fixed time to try to bring the net charge to zero. The number of times the comparator is triggered is recorded as the measure of the input signal. A single count represents 10 pC of positive charge, or the RI "least count". When we are operating the SEC with RI readout, we are constrained to use negative high voltage on the odd-numbered foils with the signal extracted from the even-numbered foils at virtual ground.

NSRL Beam characteristics

The ion beams for the SEC testing were provided by the NASA Space Radiation Facility, (NSRL) at Brookhaven National Laboratory (BNL). The NSRL beamline delivers a beam of protons or heavy ions with energies typically in the range 50 MeV/nucleon to 1000 MeV/n. It can be tuned to provide a square beam spot with good uniformity across a $20 \times 20 \text{ cm}^2$ area, or squeezed down to a 1 cm spot size with a cylindrical Gaussian profile. When running protons, beam intensities up to 10^{12} protons per spill have been utilized. With a small beam spot, it is possible to produce dose rates of several thousand

cGray per minute, a range where the ion chambers suffer from saturation and recombination. The beam at NSRL is delivered in bunches, with a single bunch coming in approximately 300ms, and a cycle time of 4 seconds.

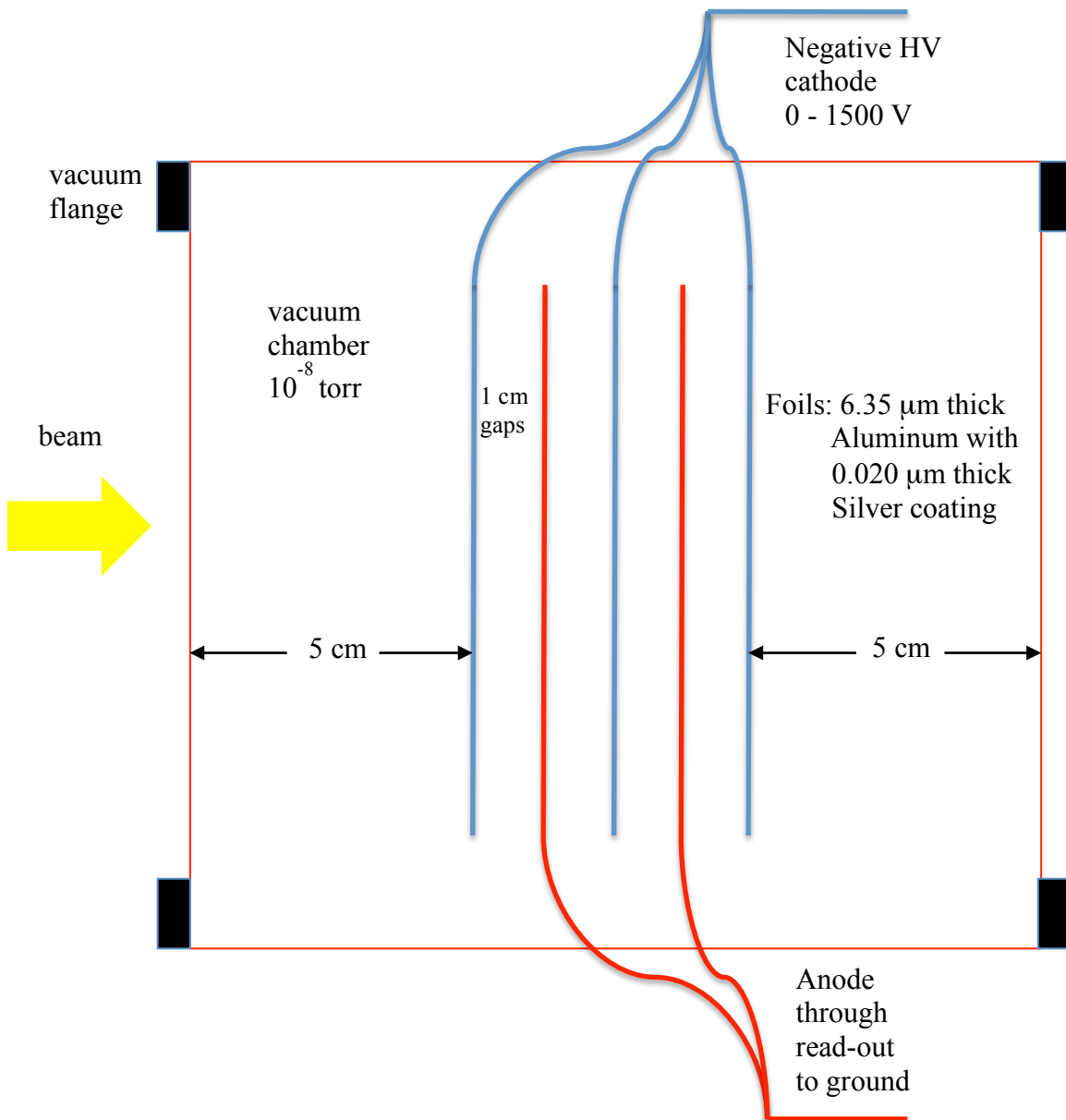


Figure 1 shows a schematic of the SEC with an entrance and exit vacuum flange, thin vacuum windows and five foils, alternating cathode and anode.

Operation of the SEC

To find the optimum operating point for the SEC, we began with a voltage scan, comparing the response of the SEC to an ion chamber (IC) that the beam passes through upstream of the SEC. The ion chamber uses the same RI system for readout as the SEC. It is filled with nitrogen gas, and has a gap of 1.02 cm. We send beam through both

chambers and calculate the ratio of the SEC response to the ion chamber response, as shown in Figure 2. As expected, the electron collection efficiency rises quickly with voltage, reaching a plateau at voltages above about 40 volts. Increasing the voltage on the SEC cathode does not increase the signal any further, and appears to decrease it slightly. The SEC response falls by nearly 5% as the voltage is increased from 40 to 1000 volts. Currently we have no explanation for the drop in response with increasing HV.

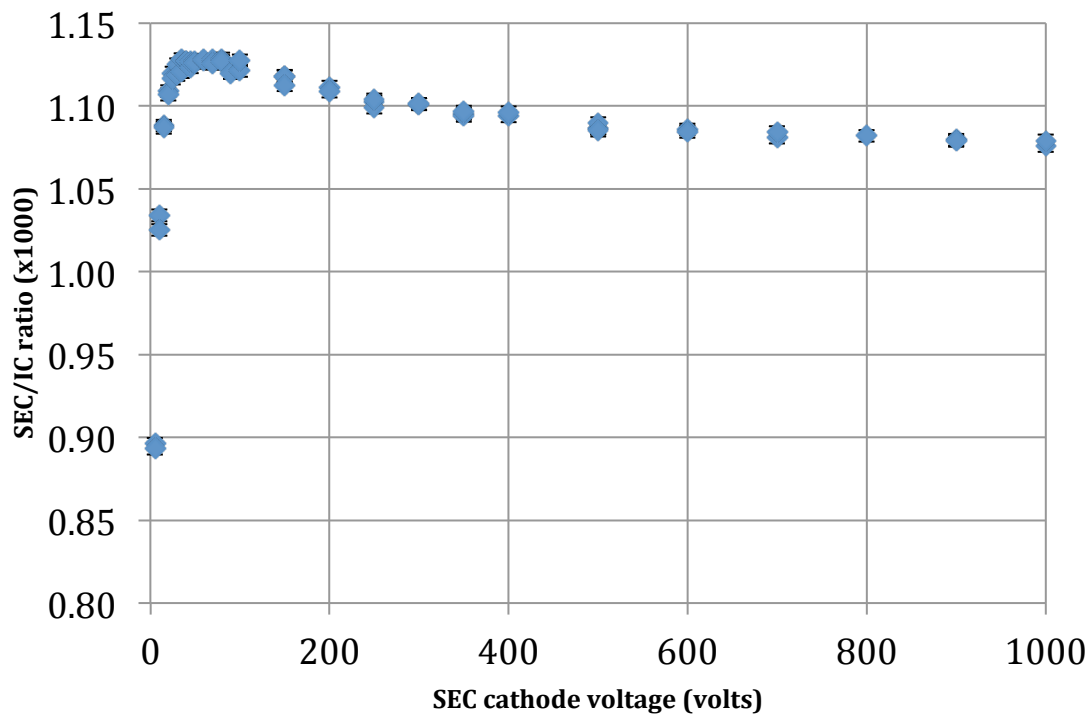


Figure 2: High voltage plateau curve for the SEC. The vertical axis is the ratio of the SEC response to the IC response, scaled up by a factor of 1000. The horizontal scale is the voltage (negative) on the SEC cathodes.

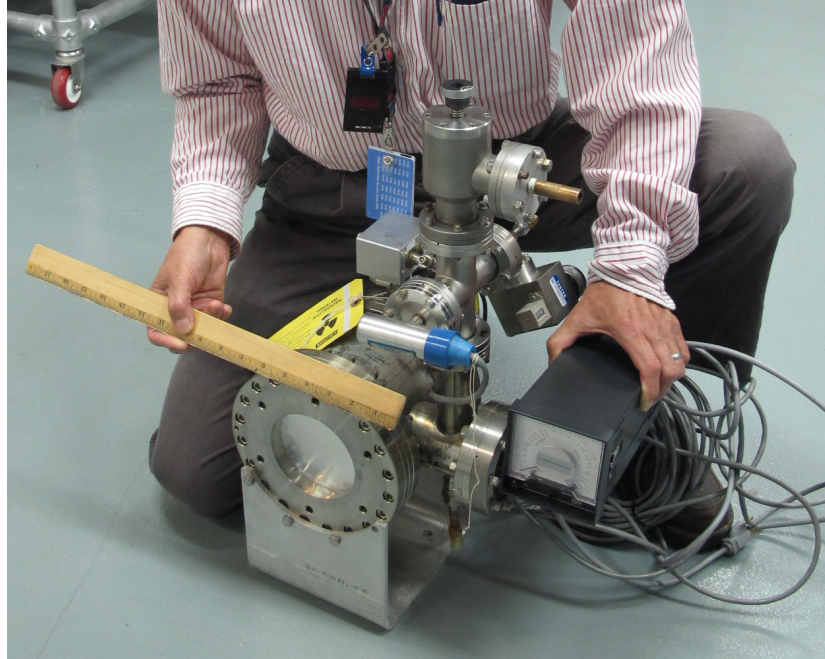


Figure 3 shows an image of the SEC, vacuum gauge, and leak valve.

Calibration of the SEC

To calibrate the SEC, we count the ions in the beam and associate the response of the SEC to that fluence of ions. Because the SEC is designed for high intensity beams, the calibration is accomplished in two stages. First, the ions in a low intensity beam are counted using a small scintillator at the same time the beam passes through a large ion chamber. This process relies upon the uniformity of the beam intensity across the collection foil of the ion chamber, so that the flux sampled by the small scintillator is an accurate measure of the total flux through the ion chamber. Once the ion chamber is calibrated, the ion beam intensity is increased and it passes simultaneously through the ion chamber and the SEC, allowing the calibration to be transferred to the SEC.

Scintillator Calibration of the ion chamber

For the calibration of the ion chamber using the scintillator, we use an Iron (Fe) ion beam because it provides a relatively large signal in the ion chamber while the beam intensity is low enough that the count rate in the scintillator has no significant dead time. The Fe beam is prepared at a kinetic energy of 963 MeV per nucleon; the highest energy Fe beam NSRL is capable of delivering. The beam spot size is tuned to be large, with a square region of uniform intensity approximately 20×20 cm in size. This beam spot is large enough to provide uniform illumination to both the scintillator and the central anode ring of the ion chamber. The area of the ion chamber ring is 154 cm^2 , compared to the 1.015 cm^2 size of the scintillator. A false color image is shown in Figure 4 where the colors indicate beam intensity. Color variations correspond to intensity variations of 3%. After preparing the beam shape, we reduce the beam intensity until the ion flux is

approximately 30,000 ions per square centimeter per spill, a rate that is well within the counting capabilities of the scintillator without significant dead time losses.

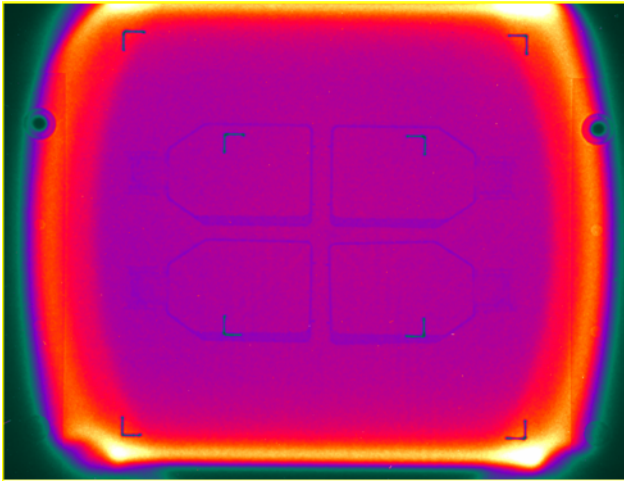


Figure 4 shows the beam intensity across the radiation field. The outer fiducial markers are 20 cm apart, and the inner markers are 10 cm apart. Intensity variations of 3% change the color of the image. This image was taken during an exposure of 4 flasks, visible by the beam scattering they produce.

The plastic scintillator is a square tile of area 1.015 cm^2 , with 0.2 cm thickness. The scintillator tile is mounted inside a paper tube and glued along the bottom edge to a cardboard disk. The paper tube is wrapped with aluminized Mylar on the inside to form an air light guide. To observe the scintillation light, a 5 cm (2") photomultiplier (PMT) is mounted on the top end of the paper tube, 30 cm from the beam center; long enough to keep the PMT out of the beam. The HV on the PMT is adjusted to give a 100 mV signal for Fe ions passing through the scintillator. The PMT signal goes to a discriminator with 30 mV threshold, and to a scaler that counts the PMT signals above threshold. The width of the discriminator pulse is set to 20 ns. This gives a counting efficiency of effectively 100% for ions passing through the scintillator, as shown in Figure 5. For all ions except protons, the pulses from the scintillator are far enough above the background that there are no non-beam related counts. When running protons, we observed that gammas, primarily from air activation, are capable of firing the discriminator. To reduce these backgrounds when running protons, we replaced the single scintillator tile with a pair of overlapping tiles that are 2 cm^2 and 1 cm^2 in size. The output of the two PMTs are discriminated and put into a two-fold coincidence. Only two signals occurring at the same time are counted by the scaler, thereby removing most gammas and any other background counts.

Relative Trigger Discriminator Efficiency

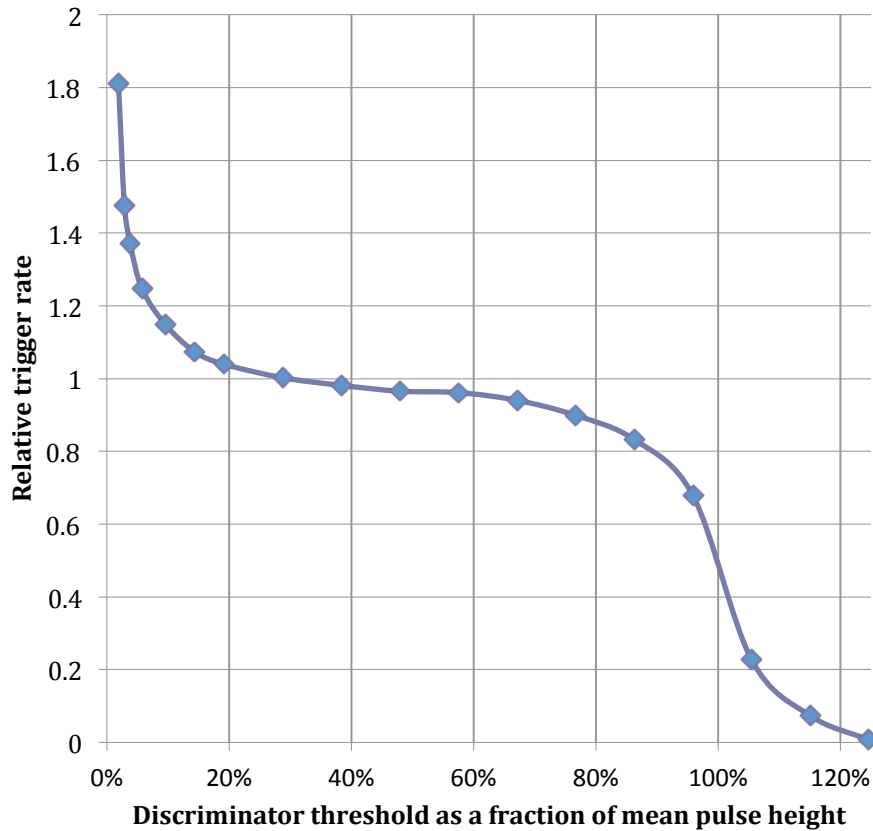


Figure 5: The threshold of the trigger discriminator is set to 30 mV for a mean pulse height of 100 mV for each ion species. The vertical axis shows the trigger rate, relative to the 30 mV rate, for different discriminator threshold settings. The horizontal axis shows the discriminator threshold, relative to the mean pulse height for the ion species. At a value of 100%, the threshold is in the middle of the ion peak, giving a trigger rate of 0.5 of the 30% setting (30 mV). The plateau is not flat because of a small amount of fragmentation of the Fe beam as it passes through the vacuum window and other material in the beamline. The fragments with nuclear charge $0 < Z < 26$ produce a continuum of pulse heights below the Fe peak.

The basic ionization chamber used in biomedical dosimetry at NSRL consists of three foils, 25 μm thick Kapton with 20 nm thick Au on one side and 1 oz/ft² Cu (35 μm thick) on the other, mounted in a gas-tight aluminum housing. Two 25 μm thick Kapton H windows complete the gas (N_2) seal. The thickness of the gas volume is 1.02 cm, for normally incident tracks. The housing is square with an inner clear width of 39 cm, an outer width of 61 cm, and a thickness of 4 cm. The ion collection surface, called the central anode ring, is a disk of diameter 14 cm, for a collection area of 154 cm².

After measuring the HV plateau of the SEC shown in Figure 2, we selected 1000 volts as the operating voltage for the SEC. The SEC is placed centered on the beam line, 20 cm downstream of the ion chamber.

An exposure of ten spills is taken with the 963 MeV/n Fe beam, and the accumulated scintillator and ion chamber counts are recorded. We account for the thickness of the ion chamber, the area ratio of scintillator to ion chamber assuming the beam intensity is uniform across the ion chamber, and we use the least count calibration of the Recycling Integrator to derive the number electrons collected for each Fe ion traversing one centimeter of N₂ operating gas in the ion chamber at standard temperature and pressure (STP). Since the 963 MeV/n Fe ions are not quite minimum ionizing, which occurs for Fe ions at a kinetic energy of 2250 MeV/n, we calculate the number of electrons that would be produced by a minimum ionizing Fe ion from the ratio of energy loss rates is $(\frac{dE(2250)}{dx} / \frac{dE(963)}{dx}) = 0.9187$. To obtain the energy loss rate for protons, we scale by the square of the ratio of nuclear charges. This gives $M_p(\text{STP}) = 57.3 \pm 1.9$ electrons for the ionization produced by a singly charged minimum ionizing proton (MIP) traversing one cm of N₂ at STP. The steps in this calculation are summarized in Table 1. This result can be compared to the number of ion pairs per unit path length in N₂ reported by Sauli [3], which is $M_p(\text{STP}) = 56$ electrons per minimum ionizing proton at STP. The largest uncertainty is due to the assumption that the beam intensity across the ion chamber is uniform. By measuring the beam profile more carefully, this uncertainty could be reduced.

The calibration of the ion chamber has been crosschecked at high dose rate using a small (1 cm³) ion chamber (EGG Counter) with a NIST-traceable dose calibration. Using the Recycling Integrator System to read out both the large ion chamber and the EGG Counter, we can determine the number of electrons generated by the passage of the beam, and relate this to the total delivered dose. This dose-based calibration method yields results that are consistent with the scintillator-based method. Both methods rely on a uniform beam profile across the ion chamber.

Transferring the Ion Chamber Calibration to the SEC

To transfer the calibration from the ion chamber to the SEC, we deliver a proton beam through both and compare the number of electrons collected in each detector. This gives the calibration of the SEC in terms of electrons produced per minimum ionizing proton.

Beam Spot Size

Before the calibration can be completed, however, it is necessary to ensure that systematic variations do not affect the response of the SEC or ion chamber significantly. The first issue to be studied was the size of the beam profile. The NSRL beamline was changed to deliver an Fe beam of 1000 MeV/n. The beam profile was focused down to a small spot, approximately 1.7 cm full width at half maximum (FWHM) so as to be fully contained within the entrance window of the SEC. In order to understand the effect of the beam spot size on our results, the spot size was varied and the ratio of the signal in the SEC to the ion chamber was plotted in Figure 6.

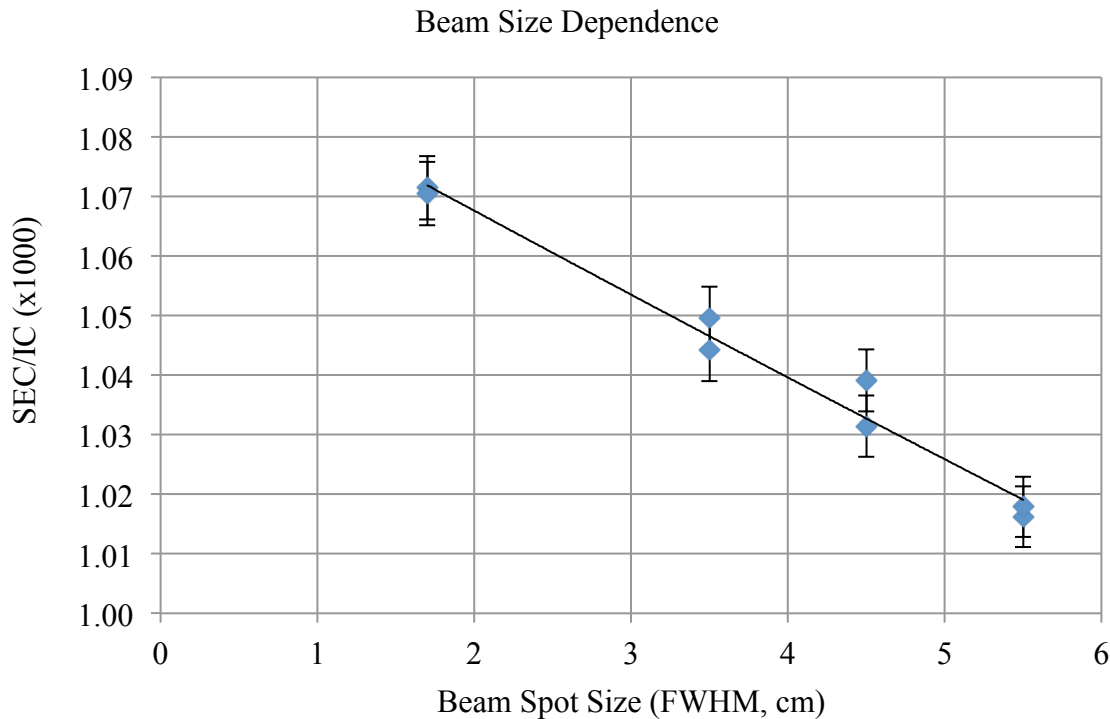


Figure 6: Variation of the ratio SEC/IC as a function of beam spot size, scaled up by a factor of 1000. The horizontal scale is the size of the beam spot full width at half maximum, in cm. An Fe beam of 1000 MeV/n was used for this study.

The aperture of the SEC is 10.16 cm, formed by the stainless steel flanges that hold both the vacuum windows and the five thin foils that make up the SEC. For large beam spots, there will be no electrons collected by the SEC for ions that hit the flanges, whereas there will in general be signal in the much larger IC. It is apparent from Figure 6 that even relatively small spot sizes of 3 or 4 cm FWHM produce a slight loss of SEC signal. Attempts to fit the loss profile assuming a Gaussian beam profile were unsuccessful. Evidently the beam has a flatter profile than a Gaussian one. In order to minimize the correction for these losses during the calibration measurement, we worked with the smallest possible beam spot size; approximately 1.5 cm FWHM for the 1000 MeV proton beam.

Dose Rate Considerations

At high rates where the SEC is designed to work well, the IC experiences saturation and recombination of electron/ion pairs. The ionization in the operating gas of the IC saturates, and the observed ionization no longer scales linearly with the deposited energy. This effect shows up as an increase in the SEC/IC ratio that we measure. An Fe beam was prepared at 1000 MeV/n, focused down to a small spot size of 1.6 cm diameter. Figure 7 shows the expected behavior for dose rates in excess of 3 Gray per spill. For measurements below 3 Gray per spill, the IC response will be an accurate measure of the deposited energy.

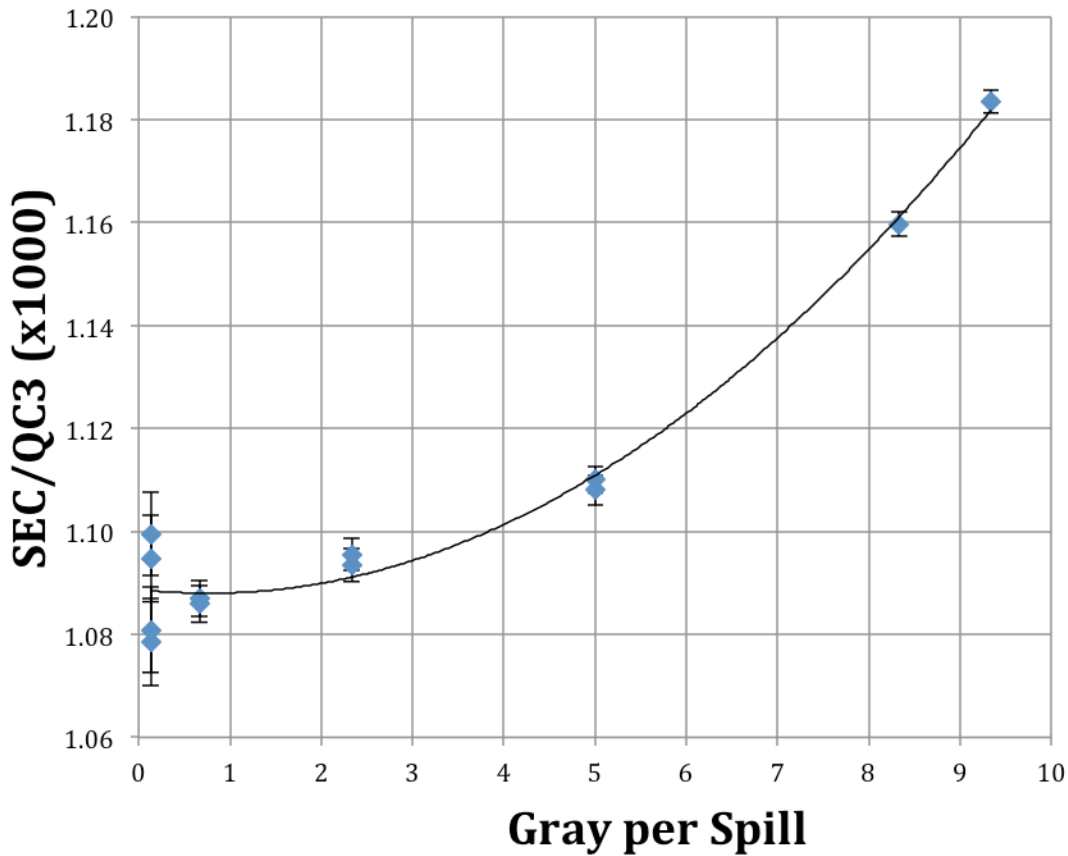


Figure 7: The SEC/IC ratio as a function of the dose rate measured in Gray per spill. Measurements were taken using a Fe beam of 1000 MeV/n.

Calibration with Protons

For purposes of the calibration, a proton beam of 1000 MeV was prepared. The beam intensity was adjusted to below 0.1 Gray per spill. The beam spot was focused down to a Gaussian profile of FWHM of 1.6 cm. A high voltage scan reproduced the plateau behavior seen in Figure 2. The calibration was performed at 1000 volts on the SEC. The beam passed through the IC and into the SEC. Both devices were read out simultaneously using the recycling integrator.

During the exposure, the ratio of the SEC signal to the IC signal was 1.23×10^{-3} . As long as the systematic uncertainties can be kept under control, this ratio is reproducible to the per cent level. Scaling to the IC calibration, this corresponds to an SEC response of $7.1 \pm 0.2 \times 10^{-2}$ electrons per minimum ionizing proton.

This result reflects the construction of the SEC with five foils, or four collection surfaces. The final step in the calibration is to calculate the SEC response per foil. This corresponds to $1.76 \pm 0.62 \times 10^{-2}$ electrons per minimum ionizing proton per foil.

Summary

We have studied the performance of a Secondary Emission Chamber, and identified a procedure yields an accurate and reproducible calibration of the device. The calibration is based on counting the flux of ions with a plastic scintillator. The scintillator counts are used to calibrate the response of an ion chamber, which in turn is used to calibrate the response of the SEC to minimum ionizing proton tracks.

As long as systematic effects such as the beam spot size and dose rate can be minimized, this procedure for the calibration of Secondary Emission Chambers can be accomplished to the level of 3-4% absolute.

In situations where it is necessary to measure the flux of a high intensity beam of protons or heavy ions, the SEC can be used. With a detection efficiency of just under 2% per minimum ionizing proton, the SEC can be the ideal instrument.

Acknowledgements

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References

- 1) Peter Yamin and Louis Repeta; Tests of a new secondary emission chamber at the AGS, IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979.
- 2) Peter Oddo, A. Rusek, T. Russo; Linearizing the response of the synchronous NSRL Recycling Integrators, published in the Proceedings of the Particle Accelerator Conference PAC-2005-RPAP004, C0505161 (2005) 2830.
- 3) Fabio Sauli, Principles of operation of multiwire proportional and drift chambers, Issue 9, CERN Series, 1977.

Appendix I

The details of the calculation of the ion chamber calibration using ion counting are presented below.

- 1) An exposure of ten spills is taken using a beam of Fe ions at 963 MeV/n, and the scintillator and ion chamber counts are recorded. The total number of Fe ions passing through the scintillator is $N_{\text{Fe}} = 1.481 \times 10^6$.
- 2) Accounting for the size of the scintillator, $A_{\text{Sc}} = 1.015 \text{ cm}^2$, this represents $\Phi_{\text{Fe}} = N_{\text{Fe}}/A_{\text{Sc}} = 1.459 \times 10^6 \text{ Fe ions per cm}^2$.
- 3) Scaling by area, assuming beam uniformity, this corresponds to $N_{\text{IC}} = \Phi_{\text{Fe}} * A_{\text{IC}} = 2.247 \times 10^8$ ions passing through the central anode ring, which has an area of $A_{\text{IC}} = 154 \text{ cm}^2$. During the same exposure, the ion chamber hardware sum records $S_{\text{IC}} = 1.565 \times 10^5$ counts, or $Q_{\text{IC}} = S_{\text{IC}} * C_{\text{RI}} = 1.565 \times 10^6 \text{ pC}$ from the central ring which has an area of $A_{\text{IC}} = 154 \text{ cm}^2$, where $C_{\text{RI}} = 10 \text{ pC/count}$. This corresponds to $E_{\text{IC}} = Q_{\text{IC}} * C_{\text{pC}} = 9.767 \times 10^{12}$ electrons, where $C_{\text{pC}} = 6.241 \times 10^6 \text{ electrons per pC}$. This means that each Fe ion produces $E_{\text{Fe}} = E_{\text{IC}} / N_{\text{IC}} = 4.346 \times 10^4$ electrons per Fe ion in the N_2 of the ion chamber. After accounting for the $t_{\text{IC}} = 1.02 \text{ cm}$ thickness of the ion chamber gas volume, this converts to $\epsilon_{\text{Fe}} = E_{\text{Fe}} / t_{\text{IC}} = 4.261 \times 10^4$ electrons per Fe ion per cm in the N_2 of the ion chamber. The 963 MeV/n Fe ions are not quite minimum ionizing, which occurs for Fe ions near $E_{\text{MI}} = 2250 \text{ MeV/n}$. The ratio of ionization levels is $(\frac{dE(2250)}{dx} / \frac{dE(963)}{dx}) = 0.9187$, which gives $M_{\text{Fe}} = 3.914 \times 10^4$ electrons per minimum ionizing Fe ion per cm travel through N_2 . Scaling by Z^2 we obtain $M_{\text{p}} = M_{\text{Fe}} Z_{\text{p}}^2 / Z_{\text{Fe}}^2 = 57.9$ electrons for the ionization produced by a singly charged minimum ionizing proton (MIP) per cm traversing N_2 . Lastly we must account for the ambient temperature and pressure of the target room, for which the correction factor scales with $C_{\text{TP}} = (P_0/P) \times (T/T_0) = 0.99$, where $P_0 = 760 \text{ mm Hg}$, and $T_0 = 295 \text{ Kelvins}$ define standard temperature and pressure (STP). This gives a value of $M_{\text{p}}(\text{STP}) = 57.3 \pm 1.9$ electrons per MIP at STP. The steps in this calculation are summarized in Table 1, along with the contributions to the uncertainty.

Table 1: Details of the calculation of the calibration of the ion chamber using ion counting.

Description	Value	Fractional Uncertainty
Number of Fe ions passing through scintillator, N_{Fe}	1.481×10^6	0.030 (from beam nonuniformity)
Scintillator Area, $A_{\text{Sc}}, \text{cm}^2$	1.015	0.010
Ion flux, $\Phi_{\text{Fe}} = N_{\text{Fe}}/A_{\text{Sc}}$	1.459×10^6	0.032
Ion Chamber Area, $A_{\text{IC}}, \text{cm}^2$	154	0.003
Ions in the IC, $N_{\text{IC}} = \Phi_{\text{Fe}} A_{\text{IC}}$	2.247×10^8	0.032
Ion Chamber reading, S_{IC}	1.565×10^5	0.000
RI conversion, $C_{\text{RI}}, \text{pC/count}$	10	0.001
Ion Chamber charge, $Q_{\text{IC}} = S_{\text{IC}} C_{\text{RI}}$	1.565×10^6	0.001

Electrons per pC, C_{pC}	6.241×10^6	0.000
Ion Chamber electrons, $E_{IC} = Q_{IC} C_{pC}$	9.767×10^{12}	0.001
IC electrons per Fe ion, $E_{Fe} = E_{IC} / N_{IC}$	4.346×10^4	0.032
Thickness of the ion chamber, t_{IC} , in cm	1.02	0.01
IC electrons per Fe ion per cm, $\epsilon_{Fe} = E_{Fe} / t_{IC}$	4.261×10^4	0.033
Ratio of LET for minimum ionizing Fe and 963 MeV/n, $(\frac{dE(2250)}{dx} / \frac{dE(963)}{dx})$	0.9186	0.001
IC electrons per minimum ionizing Fe ion per cm, $M_{Fe} = (\frac{dE(2250)}{dx} / \frac{dE(963)}{dx}) \epsilon_{Fe}$	3.914×10^4	0.033
IC electrons per minimum ionizing proton per cm, $M_p = M_{Fe} Z_p^2 / Z_{Fe}^2$	57.9	0.033
Temperature and Pressure correction, $C_{TP} = (P_0/P)(T/T_0)$	0.99	0.005
IC electrons per minimum ionizing proton per cm, $M_p(STP) = C_{TP} M_p$	57.3	0.034
Ratio of response of SEC at 1000 volts to IC	1.23×10^{-3}	0.01
SEC electrons per minimum ionizing proton	0.071	0.035
SEC electrons per proton per foil	1.76×10^{-2}	0.035