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Faraday cup monitor for the Iowa State College synchrotron electron beam

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FARADAY CUP MONITOR FOR THE IOWA STATE COLLEGE SYNCHROTRON ELECTRON BEAM

By
Roderick D. Riggs
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December 1957

Ames Laboratory
Iowa State College
Ames, Iowa

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F. H. Spedding, Director, Ames Laboratory.

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FARADAY CUP MONITOR FOR THE IOWA STATE COLLEGE SYNCHROTRON ELECTRON BEAM*

Roderick D. Riggs and C. L. Hammer

ABSTRACT

The design, construction, and testing of two high energy electron beam monitors are described. The one, a Faraday cup, is an absolute measuring device and the other is secondary emission monitor. The procedure and results necessary to calibrate the secondary emission monitor against the Faraday cup are included. Since the secondary emission monitor is portable, it is an adaptable instrument for the absolute measurement of high energy electron beams after it has been so calibrated.

*This report is based on an M. S. thesis by Roderick D. Riggs submitted December, 1957, to Iowa State College, Ames, Iowa. This work was done under contract with the Atomic Energy Commission.
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I. INTRODUCTION

Since the Iowa State College Synchrotron is adapted for extraction of the internal electron beam, it has become important to obtain a beam monitor to measure the quantity of electrons this extraction procedure yields. Two beam monitors have been designed and constructed, one a Faraday cup and the other a secondary emission monitor. The Faraday cup is essentially a large hollowed-out cylinder of lead upon which the electron beam is allowed to strike. The cup is of sufficient proportions to collect all of a 100-Mev electron beam and its associated shower. The secondary emission monitor, in contrast to the Faraday cup, is designed to be portable and more adaptable to various experimental situations. It functions by measuring the charge due to collected secondary electrons that are given off from thin metallic foils when a high energy electron beam is incident upon them. It is possible to calibrate this secondary emission monitor (SEM) by measuring the charge it collects compared to the total charge collected in the Faraday cup for the same primary electron beam.

When it is established that the Faraday cup is an absolute standard and the SEM has been calibrated against this standard, it is then possible to use the SEM independently as an instrument for measuring the absolute charge of an incident electron beam.
II. DESIGN AND CONSTRUCTION PROCEDURE

A. Faraday Cup

The function of a Faraday cup is to collect the entire charge caused by an incident electron beam. At high energies this means a considerable quantity of material is necessary to collect a shower of electrons generated by such a high energy beam. The absolute accuracy demanded of the cup thus determines the quantity and configuration of the material necessary to collect the electron beam for any given energy. Since the Iowa State College Synchrotron is capable of producing 100-Mev electrons, this is the maximum energy considered in the determination of the parameters of the Faraday cup. Fig. 1 shows the Iowa State College Faraday cup with the SEM attached in the position for calibration.

Since it is desirable to keep the Faraday cup as small as possible and still collect a high percentage of incident charge, a high density material such as lead must be used in the construction in order to stop the penetrating shower.

The work of Hofstadter and Kantz, on electron induced showers is an invaluable guide in establishing the dimensions of the Faraday cup. A summary of their results for carbon and lead is shown in Figs. 2, 3, and 4. The curves in Figs. 3 and 4 show the depth and radius of a cylinder required to capture a given percentage of the incident electron beam

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Fig. 1. Faraday cup and secondary emission monitor.
Fig. 2. Differential curve showing the longitudinal development of an electron-induced shower in carbon and lead. The slope of the transition curve after the shower maximum corresponds to the minimum absorption coefficient for gamma rays in the medium.
Fig. 3. Isoenergetic curves for carbon. These data show the dimensions of a cylinder of carbon required to absorb a given fraction of the incident electron energy.
Fig. 4. Isoenergetic curves for lead. These data show the dimensions of a cylinder of lead required to absorb a given fraction of the incident electron energy. A 45 degree line was drawn to each isoenergetic curve from the point of intersection of its "asymptotes". The solid curve passing through the intersections of the 45 degree lines with their respective isoenergetic curves defines the optimum dimensions of an absorbing cylinder as used in the design of the Faraday cup.
at 185 Mev. From Fig. 4 it is determined that a cylinder of lead with a depth of 29 radiation lengths and a radius of 29 radiation lengths will capture more than 99 per cent of the energy in a 100-Mev electron beam.

The percentage of charged particle loss is the important quantity, and it is desirable to make an estimate of what this particle loss is for the dimensions of the Iowa State Faraday cup. Using the data of Hofstadter and Kantz, Brown and Tautfest have derived an equation that has been verified experimentally with the two Stanford University Faraday cups in the energy range 30-250 Mev.

The percentage of charged particle loss by penetration from a Faraday cup consisting of t radiation lengths of carbon backed by x radiation lengths of lead is given by

\[ f_p = 2E_0 \left( 1 - \frac{D}{E_0} \right) \exp \left[ -\sigma(x - \ln \frac{E_0}{185}) \right] \text{ per cent.} \quad (1) \]

The value of \( D \) is \((10 \ln E_0 + 53)\) Mev/radiation length; \( \sigma \) for lead is .236 radiation lengths; and \( E_0 \) is the energy of the incident electron beam in Mev. Using the dimensions of the carbon and lead in the Iowa State Faraday cup (Fig. 1) in Eq. (1), \( f_p = 0.2 \) per cent for \( E_0 = 100 \) Mev. Since the Faraday cup is usually used with energies less than 100 Mev, the loss due to shower penetration is indeed negligible.

In addition to losses due to shower penetration, there can also

---

be a loss due to backscattering of electrons out the mouth of the cup. Three procedures are adopted for reducing this possible source of error. First, the geometry of the front of the cup is made re-entrant as shown in Fig. 1. The diameter of the opening must be large enough to accept the primary electron beam after its passage through the SEM, but it should be small enough to reduce significantly the solid angle for electrons backscattering out of the cup. Second, the bottom of the Faraday cup, where the electrons first strike, is made of low-Z material (e.g., carbon) to minimize the cross-section for backscattering. The last procedure is to insert a permanent magnet around the bottom of the Faraday cup aperture to prevent low energy backscattered electrons from escaping out the mouth of the cup.

It is possible to make an estimate of the error introduced by these backscattered electrons for a given primary electron beam. Using the relativistic Rutherford cross-section $\sigma(\theta)$ for single scattering, the error is given by

$$\text{error} = \frac{\int_{\theta_1}^{\pi} \sigma(\theta) \sin \theta \, d\theta}{\int_{0}^{\pi} \sigma(\theta) \sin \theta \, d\theta}$$  \hspace{1cm} (2)$$

where $\theta_1$ is the minimum angle subtended at the mouth of the cup by an electron spot at the bottom of the cup. $\theta_0$ is the cut-off angle, taking into consideration the effect of the shielded coulomb force$^1$ since the

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Rutherford cross-section equation does not hold at $\theta = 0^\circ$. For an electron spot of 4-in. diameter, $\theta_1 = 160^\circ$. $\theta_0$ is less than $1^\circ$ for an electron of 10 Mev. The error is found to be less than 0.0003 per cent for this energy. This is negligible for the energy range of interest since the error decreases as energy increases. The diameter of the electron spot is actually smaller than 4 in., which further decreases the error.

The probability of an electron escaping by plural scattering is small compared to the probability of escape by single scattering. The plural scattering will be of a lower energy and influenced by the field of the permanent magnet. Any scattered electron of energy less than 1 Mev will be bent back into the lead portion of the Faraday cup.

Loss of charge due to leakage currents is reduced by properly insulating the Faraday cup from ground. Also an "automatic slide-back" electrometer is used in conjunction with the calibrated condenser; so the input voltage is greatly reduced and hence reduces the effect of any leakage resistance.\(^a\)

Collection of ions is minimized by enclosing the cup within a vacuum envelope. The vacuum maintained depends upon the absolute accuracy demanded of the Faraday cup. Mechanical fore-pump pressures are not adequate; so high vacuum techniques are required. If one requires that less than 0.01 per cent of the collected charge be neutralized by positive ions, than a pressure of $10^{-5}$ mm of Hg or less is necessary.\(^1\)

The cup is constructed by pouring approximately 900 lbs. of lead

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\(^a\)Discussed in detail in section III.

into a steel jacket which is then machined to allow the insertion of a cylindrical shaped magnet into the interior. A sleeve of lead is placed adjacent to the magnet, completing the cup. A thin layer of 1/16-in. brass is soldered in place to seal off completely the lead and magnet from the vacuum chamber; hence the out-gassing of the lead is not a problem in the attainment of high vacuum.

The 4-in. graphite plug\(^a\) is inserted into the opening of the cup. The entire cup is supported on an aluminum cradle insulated from the stainless steel vacuum shell by a 1/8-in. polystyrene sheet bent to fit the geometry of the interior. The incident electrons are attenuated in the graphite, and any photons produced are effectively absorbed by the lead.

An aluminum foil of thickness 1.71 mg/cm\(^2\) is placed over the opening of the cup and insulated from the cup by nylon stand-offs, where it can either be used as a bias plate or as a "cap" for the cup when it is electrically connected to the cup by the type-N pressure fittings on the exterior of the stainless steel shell. The vacuum system is connected as indicated in Fig. 1, and the entire system is maintained at a pressure of 5 x 10\(^{-7}\) mm Hg when in operation.

B. Secondary Emission Monitor

The device most commonly employed to monitor beams of ionizing

\(^a\)Plug was a cylinder of pile graphite.
radiation is the ionization chamber. It is simple in conception, easy to construct, and reliable in operation. When carefully calibrated, it is a stable absolute monitor and, as such, is in general use in the measurement of total integrated flux. It has the useful property in the measurement of low intensity beams of a gain of 30-60 per cm of path depending on pressure and type of gas used and the energy of the primary ionizing particle. However, above a certain beam current density, the charge collected is no longer a linear function of the flux of primary particles; and the chamber is said to saturate. The extent of saturation is a function of the geometry of the chamber, the strength of the electric field, and the density and type of gas used.

Extension of the linear range of such a chamber is commonly achieved by reducing the density of the counting gas and/or increasing the electric field. The limit of the first process is an evacuated chamber in which provision is made to collect the secondary electrons ejected from the entrance foil by the passage of the primary beam. By using thin foil and high vacuum techniques, it is possible to design a counter which leaves the primary beam virtually unaffected as it courses the chamber and still yields secondary electrons in sufficient quantity to give an accurate measure of the primary beam intensity when a current integration is made.

To eliminate any cable polarization effects, a three element electrical connection is used in the SEM design as illustrated in Fig. 1. By allowing the collecting voltage to appear between the emitting foils and a grounded set of foils separated by the collecting foils, no po-
Fig. 5. Secondary emission monitor.
tential difference appears between the collecting plate and ground. Thus cable polarization effects are reduced to zero.\textsuperscript{a}

To eliminate the possibility of high energy secondary electrons penetrating the aperture of the Faraday cup after being produced in the SEM, a second cylindrical magnet must be placed between the SEM and the cup to spin out these undesirable electrons. A magnet capable of bending a 1.25-Mev electron out of the region between the two instruments is considered adequate according to the arguments given by Tautfest and Fechter.\textsuperscript{1}

The thin aluminum foils (1.71 mg/cm\(^2\)) are cemented to open brass rings which are inserted into three slotted teflon rods with a foil spacing of 0.1 in. The entire assembly consisting of 21 such foils is inserted into a 5-in. brass pipe flanged at either end to facilitate its mounting to the front of the Faraday cup. The aluminum foils are electrically connected by short silver wires. The electrical connections to the emitting and collecting foils of the SEM are made through the brass chamber with Stupakov feed-through connectors, which in turn are connected to type-N coaxial fittings.

\textsuperscript{a}The error voltage of the "slide-back" electrometer is the only voltage across the collecting cable and is less than a millivolt.

III. ELECTRONICS

The basic electronic circuit used in conjunction with the Faraday cup is shown in Fig. 6. The components enclosed within the dotted lines are within the interior of the model NA100 Curtiss-Wright 1000 cps dynamic capacitor electrometer. This is an "automatic slide-back" electrometer which keeps the cup potential within a millivolt of ground potential, thereby reducing the effect of the leakage resistance $R_s$ and shunt capacity $C_s$.

One can analyze the electronic circuit in the following way. Assume a constant charge per unit time is being accumulated in the Faraday cup. This develops a certain D.C. voltage $V$ across the dynamic capacitor $C_E$. The capacity of $C_E$ is changing slightly at the frequency of 1000 cps; so a certain portion of this voltage $V$ is being converted into an A.C. signal and is amplified by the amplification factor $A$. The voltage appearing at the output of the amplifier is

$$V_o = V_f A$$

where $f$ is the conversion efficiency of the dynamic capacitor.

This voltage is developed across the meter and the voltage divider such that the negative voltage that appears at the bottom of the condenser $C_{ll}$ is

$$V_{nl} = rV_f A$$
Fig. 6. Electrometer number 1 with essential circuit components.
where \( r \) is the gain of the voltage divider network and is a function of the scale setting of the electrometer. This negative voltage tends to drive the bottom of \( C_{L1} \) negative, effectively pulling the input of the electrometer to a voltage of \((V - V_{N1})\) above ground. The so-called error voltage \((V - V_{N1})\) is very nearly zero and is the reason for the reduction in the effect of the leakage resistance \( R_S \) and the shunt capacity \( C_S \). The instrument has been previously calibrated such that the meter reads exactly the value of \( V_{N1} \) for a voltage input \( V \).

The equation for current flow in such a network can be written as

\[
I = \frac{Q_1}{t} = \frac{V}{R_S} + V(C_E + C_S) + V C_{L1} - (-rFAC_{L1})
\]

where \( t \) is the time to accumulate the charge \( Q_1 \). For a constant \( I \) this is merely a linear differential equation in \( V \) with a solution:

\[
V = I R_S \left[ 1 - e^{-Bt} \right]
\]

where it is assumed that at \( t = 0, V = 0 \) and

\[
B = \frac{1}{C_E + C_S + C_{L1} + C_{L1}} R_S
\]

Since the meter reads the voltage \( rVfA \), one can write an expression for a nominal charge \( Q_{N1} \) as

\[
Q_{N1} = rVfAC_{L1} = V_{N1}C_{L1}
\]
Equation (6) can be rewritten as

$$\frac{Q_{N1}}{rfAC_{L1}} = \frac{Q_1}{t} R_S \left[ 1 - e^{-Bt} \right]$$

where \( \frac{Q_1}{t} = I \).

Expanding the exponential, keeping just the terms to second order, and re-solving Eq. (9) for \( Q_1 \) yields

$$Q_1 = Q_{N1} \frac{1}{rfAC_{L1} R_S \left[ B - \frac{B^2 t}{2} \right]}.$$  

Substituting in the value for \( B \),

$$Q_1 = Q_{N1} \frac{1 + \frac{1}{rfA} \left[ 1 + \frac{C_E + C_S}{C_{LL1}} \right]}{1 - \frac{2R_S \left[ C_E + C_S + C_{LL1}(1 + rfA) \right]}{t}}.$$  

The value of \( R_S \) is experimentally determined by placing a sensitive micro-micro-ammeter in series with \( R_S \) and a voltage of 620 volts D. C. \( R_S \) is found to be \( 10^{12} \) ohm \(< R_S < 10^{13} \) ohm. The factor \( 1/rfA \) is referred to as the capacity reduction factor and is given in the instruction manual of the equipment as \( 4 \times 10^{-3} \). By varying the value of \( C_S \) a known amount and measuring the corresponding change in time to accumulate a pre-assigned voltage with a constant current input, it is possible to determine experimentally the capacity reduction factor. It is found to be \( 4 \times 10^{-3} \).

Using these values for \( 1/rfA \) and \( R_S \), one is now able to neglect the second term in the denominator of Eq. (11) when \( t \) is less than 2000
seconds as is the case in the experiment. Eq. (11) can then be written as

\[ Q_1 = Q_{N1} \left[ 1 + \frac{1}{rfA} \left( 1 + \frac{C_E + C_S}{C_{L1}} \right) \right]. \] (12)

The capacity \((C_E + C_S)\) is easily measured with an impedance bridge and found to be equal to \(3.55 \times 10^{-12} \text{ F.}\) \(^a\) For \(1/rfA = 4 \times 10^{-3}\) and \(C_{L1} = 0.01045 \times 10^{-6} \text{ F}\) (to within an error of \(\pm 1\) per cent), \(^a\) the correction term to \(Q_{N1}\) is of the order of 0.4 per cent and within the experimental error in the measurement of \(C_{L1}\). Eq. (12) then reads:

\[ Q_1 = Q_{N1} = V_{N1}C_{L1}. \] (13)

\(C_{L1}\) is a low-leakage polystyrene capacitor. \(^b\)

The electronic circuit shown in Fig. 7 is used to measure the charge accumulated on the SEM and utilizes a Brown continuous balance electrometer system and attached recorder unit. This electrometer is similar to electrometer number 1 except it is a 60 cps dynamic capacitor type. It is also an "automatic slide-back" electrometer and decreases the voltage between the SEM collector foils and ground, reducing the effect of any leakage resistance \(R_S\) and shunt capacity \(C_S\).

An attempt can be made to analyze the circuit mathematically as

\(^a\)Measured on type 650-A Impedance Bridge, General Radio Co., Cambridge, Mass.

\(^b\)Manufactured by Condenser Products Corp., Newark, New Jersey.
Fig. 7. Electrometer number 2 with essential circuit components.
for electrometer number 1. Assume a constant charge per unit time is being accumulated in the SEM. This develops a certain D. C. voltage $V$ across the dynamic capacitor $C_E$. The capacity of $C_E$ is being varied a small amount at the frequency of 60 cps; so a certain portion of this voltage $V$ is being converted into an A. C. signal and is amplified by the factor $A$. The voltage appearing at the output of the amplifier is

$$V_o = VfA \quad (14)$$

where $f$ is now the conversion efficiency of the 60 cps dynamic capacitor. This voltage is developed across the windings of a two-phase motor in such a way that

$$\dot{\theta} = pV_o \quad (15)$$

where $p$ is a constant and $\dot{\theta}$ is the angular velocity of the motor. This motor is connected by a shaft to the recording indicator on the slide wire mechanism so that as the motor turns, the voltage developed on the bottom of $C_{L2}$ is given by

$$V_{N2} = KE \theta \quad (16)$$

where $K$ is a constant, $E$ is a regulated voltage and equals 105 volts D. C., and $\theta$ is the angular distance the motor turns. The voltage appearing between the input of the electrometer and ground is then
(V - V_{N2}). This reduces the effect of R_S and C_S.

Setting up the differential equation for current flow in the circuit as

\[ I = \frac{Q_2}{t} = \frac{V}{R_S} + \dot{V}(C_E + C_S) + \dot{V}_C L_2 - (-V_{N2} C_{L2}), \tag{17} \]

the equation can be solved for Q_2 as a function of V_{N2} and C_{L2}. However, one obtains a result which cannot be verified experimentally; so a different approach is taken to the problem. The SEM is replaced with a standard cell (1.018 volts D. C.) in series with a precision resistor (10^{12} ohms). It is then possible to introduce into the electrometer a constant current I of 1.018 \times 10^{-12} amperes\(^a\) to within \pm 1.0 per cent. By recording the time that such a current is being fed into electrometer number 2 and comparing this charge (It) to the nominal charge (V_{N2} C_{L2}), it is possible to determine the accuracy of the instrument when R_S and C_S are disregarded.

\[ It = V_{N2} C_{L2} \tag{18} \]

where V_{N2} is the voltage indicated on electrometer number 2. These two values of charge are found to agree to within 1.5 per cent. Attaching the SEM and associated cable in parallel with the same constant current source, it is possible to see the effect of the additional shunt capacity

\(^a\)This current is chosen because it is of the same order of magnitude as the currents obtained when using the Iowa State College Synchrotron as the source of electrons.
and leakage resistance. No change is observed. It is therefore reasonable to say that

$$Q_2 = V_{N2}C_{L2}$$

(19)

where $Q_2$ is the quantity of charge introduced into electrometer number 2.

Another way of showing that the effects of $R_S$ and $C_S$ are negligible is to connect the same constant current source ($1.018 \times 10^{-12}$ amperes) to the input of electrometer number 2. Electrometer number 1 can function as a very sensitive voltmeter, and so using it in this capacity it is possible to measure the voltage between the input of electrometer number 2 and ground. The voltage is found to be of the order of $0.5 \times 10^{-3}$ volts D.C. This means that the effective voltage across $R_S$ and $C_S$ is reduced by a factor of $10^4$; so Eq. (19) is a legitimate assumption.*

The value of $R_S$ is determined experimentally to be approximately that of the $R_S$ in electrometer number 1 ($5 \times 10^{12}$ ohms). $C_S$ is measured to be $3500 \times 10^{-12}$ F. $C_{L2}$ is a low-leakage polystyrene capacitor whose value, measured on the impedance bridge, is $0.1045 \times 10^{-6}$ F to within ±1.0 per cent.

Since electrometer number 2 reads in scale divisions and not directly in millivolts, a calibration curve (Fig. 8) is given relating the scale divisions on the 10 millivolt scale to millivolts. The experimental

---

* Voltage of $0.5 \times 10^{-3}$ volts across a resistance of approximately $5 \times 10^{12}$ ohms corresponds to a current many orders of magnitude less than the currents normally integrated. $C_S$ is also effectively reduced by $10^4$ and is negligible compared to $C_{L2}$.

b Manufactured by Condenser Products Corp., Newark, New Jersey.
Fig. 8. Calibration of electrometer number 2 on 10 millivolt scale. Millivolts D. C. versus scale divisions.
Fig. 9. Secondary current versus bias voltage for the secondary emission monitor with $^{90}$Y as the source of primary electrons.
points are determined by measuring the actual voltage across the slide wire as a function of scale division.

To determine the proper bias voltage to be applied to the SEM, the 1000-cps electrometer is connected to the SEM, which is highly evacuated,\textsuperscript{a} and a source of electrons in the form of a 10 millicurie $^{90}$Y, $\beta^-$ emitter,\textsuperscript{b} is placed in front of the SEM. By varying the bias voltage and measuring the charge collected per unit time as a function of the voltage, it is possible to determine the optimum voltage for high energy operation. A plot of secondary current versus bias voltage is shown in Fig. 9. From the curve it is evident that a bias of -620 volts is sufficient for proper collection of secondary electrons under normal operating conditions.

\textsuperscript{a}5 \times 10^{-7} \text{ mm Hg.}

\textsuperscript{b}Peak electron energy is 2.2 Mev.
IV. EXPERIMENTAL PROCEDURE AND RESULTS

It is possible to calibrate the SEM against the Faraday cup by mounting the SEM on the front of the Faraday cup as shown in Fig. 10 and allowing the primary electron beam to pass through the SEM before being collected in the Faraday cup. The ratio of the two charges thus collected as a function of energy is the quantity of interest. At the same time it is possible to get an estimate of the number of electrons per burst extracted from the synchrotron by merely recording the total charge collected in the Faraday cup in a certain time t for the given repetition rate of the machine.

Figs. 11 and 12 show the experimental arrangement for the determination of the calibration constant of the SEM and for the determination of the absolute electron beam. The source of high energy electrons is the Iowa State College Synchrotron,⁵ which delivers electrons of energy 0-63 Mev. The electrons are extracted from the synchrotron vacuum tube through a 1/16-in. lucite window into a 2 1/2-in. brass pipe. This pipe is evacuated to fore-pressure and lies along the axis of symmetry of a pair of quadrupole focusing lenses¹ designed to focus the extracted electron beam to a circular spot of less than 1-in. diameter on the foils of the SEM. As the energy of the electron beam is varied, the quadrupole lenses require refocusing to keep the focusing point a constant.

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⁵ The magnet and vacuum chamber are similar to the components described by Pollock et al., J. App. Phys. 18, 810 (1947).

Fig. 10. Secondary emission monitor, secondary electron sweeper magnet, and Faraday cup.
Fig. 11. Experimental arrangement with physical dimensions.
Using the data supplied by Lynch, a plot of quadrupole currents versus electron energy for optimum focusing is given in Fig. 13.

The 2 1/2-in. brass pipe is isolated from the high vacuum in the SEM and Faraday cup by an aluminum foil 34.2 mg/cm² thick. The aluminum foil should always be used to isolate the SEM from the synchrotron vacuum tube since this protects the delicate foils in the SEM and also insures that the SEM will be used under the same conditions under which it was calibrated. Any secondary electrons produced in the lucite window are swept out of the primary beam by the magnetic field of the quadrupole lenses, and the few secondary electrons produced in the 34.2 mg/cm² window merely enhance the response of the SEM.

Using Eqs. (13) and (19), where the same primary beam is introduced to both monitors simultaneously, it can be said that

\[ Q_2 = R Q_1 \]  

(20)

where \( Q_2 \) is the charge collected by the SEM for a charge \( Q_1 \) collected in the Faraday cup and \( R \) is some function of the primary electron energy. Then

\[ R = \frac{V_{NL2} C_{L2}}{V_{NL1} C_{L1}} \]

(21)

when the two charge measurements are made simultaneously. The values

---

Fig. 13. Quadrupole current versus electron energy.
of $C_{L2}$ and $C_{L1}$ are given in section III, and it is seen that $\frac{C_{L2}}{C_{L1}} = 10$.

Eq. (21) can be written as

$$ R = 10 \frac{V_{N2}}{V_{N1}}. $$

(22)

Using Eq. (13) and recording the time $t$ of the charge measurement with the repetition rate of the machine as 59 cps, the equation for the number of electrons per burst is given by

$$ \text{electrons per burst} = \frac{V_{N1} C_{L1}}{94 t} \times 10^{19}. $$

(23)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Energy Integrator Setting</th>
<th>$R$</th>
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<tr>
<td>19</td>
<td>190</td>
<td>0.298 ± 0.003</td>
</tr>
<tr>
<td>26</td>
<td>276</td>
<td>0.308 ± 0.004</td>
</tr>
<tr>
<td>38</td>
<td>414</td>
<td>0.300 ± 0.003</td>
</tr>
<tr>
<td>51</td>
<td>533</td>
<td>0.293 ± 0.003</td>
</tr>
<tr>
<td>63</td>
<td>635</td>
<td>0.295 ± 0.003</td>
</tr>
</tbody>
</table>

aThe data in Table represent a total of 45 separate $R$ determinations at these 5 energies.

Assuming that the experimental points of Fig. 14 describe a linear function of the form

$$ R = a + bE; $$

(24)
Fig. 14. $R$ versus energy integrator setting.
and applying a least squares analysis to the data yields the following relation:

$$R = 0.307 - 0.000020 E$$

(25)

where $E$ is the energy in integrator setting units. The slope is found to be $b = -0.000020 \pm 0.000015$. The statistical error in the energy is neglected since the energy spread of the primary beam is $\pm 10$ Kev, and the variation in the mean energy is controlled by the energy integrator to less than $\pm 100$ Kev.

Table 2. Electrons/burst as a function of energy$^a$

<table>
<thead>
<tr>
<th>Energy (Mev)</th>
<th>Electrons/burst</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>$0.7 \times 10^5$</td>
</tr>
<tr>
<td>26</td>
<td>$1.9 \times 10^5$</td>
</tr>
<tr>
<td>38</td>
<td>$2.5 \times 10^5$</td>
</tr>
<tr>
<td>51</td>
<td>$3.1 \times 10^5$</td>
</tr>
<tr>
<td>63</td>
<td>$4.7 \times 10^5$</td>
</tr>
</tbody>
</table>

$^a$These values are only approximations since the primary electron intensity fluctuates over wide limits. The values represent the best yield obtained at that particular energy.

No attempt is made to analyze the errors in the electron per burst measurements. One can only draw the general conclusion that under the present conditions the primary electron beam contains approximately $10^5$ electrons per burst.
V. DISCUSSION

The limits on the absolute accuracy in the determination of $R$ are largely determined by the possible errors in the capacity measurements $C_{L1}$ and $C_{L2}$. When the errors in the two capacities are combined with the statistical variation in $R$, one finds that $R$ is specified to approximately $\pm$ 2 per cent. This error could be reduced significantly by utilizing a more accurate measuring procedure on the capacities than has thus far been done. The statistical error in $R$ could also be reduced by increasing the number of runs at a particular energy.

The accuracy of an absolute charge measurement is largely determined by the error in the measurement of $C_{L1}$ combined with the statistical error one would have in the meter readings for a specified voltage. The error in the meter readings should not be greater than the statistical error observed in $R$ which was a combination of two meter readings. This produces a net error of approximately 1.5 per cent and is well within the accuracy of most experiments requiring a knowledge of the absolute charge.

The fact that $R$ seems to be increasing slightly as electron energy is decreased seems reasonable enough since one expects more secondary electrons as the primary electron energy is decreased. The Stanford group$^1$ found their $R$ to be essentially a constant in the energy range from 110 to 300 Mev. This does not represent a contradiction since the

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two ranges of investigation are widely separated. The Iowa State R measurements could well approach a slope equal to zero as the electron energy is increased to 100 Mev.