#### A PRECISION TOROIDAL CHARGE MONITOR FOR SLAC\*

R. S. Larsen and D. Horelick

Stanford Linear Accelerator Center Stanford University, Stanford, California

#### ABSTRACT

A charge monitor system which utilizes a ferrite toroid operated in a resonant mode is described. The system is designed to monitor electron and positron beam pulses of  $\leq 2 \mu$ sec duration having peak intensities of 50  $\mu$ A to 50 mA, at a maximum rate of 360 pps. The digital accumulator which totalizes charge is bidirectional in order to reduce the effects of noise. For runs of 10<sup>4</sup> samples (~ 30 seconds at 360 pps), the error due to noise is  $\leq 0.1$  percent of reading over a 1000:1 signal range. Faraday cup comparisons for currents greater than 1 mA peak show agreement to < 1 percent, with a standard deviation of < 0.1 percent. The system includes a built-in calibration and test facility; toroid temperature stabilization; digital displays for total charge, charge per beam pulse, and number of beam pulses; and digital outputs to a computer.

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#### I. INTRODUCTION

#### A. General

Toroidal monitors are used in many laboratories for observing the intensities and shapes of pulsed beams, and several such systems are reported in the literature.  $^{1,2,3,4}$  To date, however, although a number of different systems have been described,  $^{5,6,7,8,9,10}$  toroids have not been widely used as precision charge monitors. In general, accuracies of such systems have been no better than about 1 percent.

In very high energy accelerators such as the 20-GeV machine at SLAC, the need for a precision, non-intercepting type of charge monitor becomes imperative, particularly for use in photoproduction experiments. In 1965, Richter<sup>11</sup> suggested further development of a resonant toroid<sup>5</sup> charge measurement system, one version of which was already under construction at SLAC.<sup>6,7</sup> The new system was to be exclusively for use in the experimental area; it would if necessary employ preamplifiers very close to the toroid to minimize cable pickup noise; and it would include a digital noise-averaging system in order to achieve the highest usable sensitivity. The design goal was to achieve a system accuracy of  $\leq 0.1$  percent at an average beam current of 20  $\mu$ A, and a useful measurement range to at least 20 nA, possibly with reduced accuracy at the low end.

As the design progressed, every effort was expended to make the electronics as accurate and as stable as possible to insure reliability between calibrations. These efforts included such measures as temperature stabilization of the ferrite core of the toroid, and temperature control of the critical timing circuitry. Construction and installation of the system were completed in late 1966; over the past year, continuing study has led to further modifications and improvements. At the present time, from all data available, the system appears to meet its original design

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goals, with excellent stability and reliability. A discussion of the theory, electronics system, and overall performance, is the further topic of this paper.

#### B. SLAC Beam Characteristics

At this point it will be well to briefly review the characteristics of the SLAC beam. The electron beam pulse has a maximum amplitude and duration of approximately 50 mA and 2  $\mu$ sec respectively. The beam pulse is made up of bunches of electrons, spaced by the period of the 2856 MHz RF of the accelerator, or 0.35 nsec. Each bunch is about 30 psec in duration.

The accelerator operates at a maximum rate of 360 pps, which gives a maximum average current into the experimental area of about 36  $\mu$ A. Other repetition rates, namely sub-multiple increments of 60 pps such as 300, 240, 180, 120 and 60, are also available. Rates as low as 30, 10 or 1 pps are used in some applications.

The beam pulses are timed from a master trigger system, which also provides very stable 2  $\mu$ sec pre-triggers for use in the experimental areas. Triggers are available both at a constant 360 pps, and at the actual beam rate. The resonant toroid type of monitor is well suited to such short duration, low duty cycle, and precisely timed beams.

The SLAC machine also contains a positron source, which can at the present time deliver currents of about 2 mA peak into the End Stations. Also, as a matter of interest, the beam can be time-shared into separate experimental areas, each area receiving a beam with individual current, energy and rate characteristics; the maximum (combined) rate for all beams is 360 pps.

A further feature of the SLAC beam is that it can be "chopped" by a beam knockout system, <sup>12</sup> which is a system for extracting periodically-spaced single bunches of electrons from a normal beam. This type of beam is of especial

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value in time-of-flight experiments. Various chopping frequencies are possible, all of which are phase-coherent with the 2856 MHz RF of the accelerator; frequencies of approximately 40, 10 and 6 MHz are commonly used. In an experiment to be described in this report, the 10 MHz chopper was used, resulting in a beam of single bunches,  $\sim$  30 psec in duration, separated in time by  $\sim$  50 nsec.

#### **II.** RESONANT TOROID THEORY

#### A. <u>General</u>

There are two fundamental ways in which a toroid can be used to measure charge. One method is to terminate the toroid in a resistance to develop a voltage proportional to instantaneous beam current, and then to electronically integrate the voltage waveform to obtain a measure of charge. This type of monitor is presently in use for monitoring charge at 30 points along the SLAC two-mile accelerator;<sup>10</sup> in this system, the best accuracy obtained is approximately 1 percent, and long term stability of that order appears difficult to maintain.

The second method, as described in Refs. 5, 6, 7 and 9, is to load the toroid winding with a capacitor so as to cause it to resonate when a pulsed current passes through the core. In this manner, a low frequency voltage proportional to beam charge is developed at the toroid terminals; the waveform is then amplified and sampled at one of its peaks to obtain a measure of charge.

#### B. Equivalent Circuit Analysis

Figure 1 (a) shows the toroid geometry, including the relative spacing of electron bunches in a normal beam, and Fig. 1 (b), the circuit model which was used in the analysis.<sup>7,9</sup> The toroid is considered to be an ideal current transformer, with the beam equivalent to a single-turn primary. Since we are concerned only with the amount of charge which flows into the capacitor upon passage

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of a beam pulse, such factors as stray inductance and capacitance of the toroid winding are unimportant in the analysis.

The equivalent circuit analysis assumes a rectangular beam pulse containing a total charge  $I_bT$ , where  $I_b$  is the peak beam current, and T the pulse duration. The corresponding current referred to the toroid output is thus  $I_b/N$ , and the charge is  $(I_b/N)T$ .

In the following analysis, R is an external damping resistance which is assumed to include the effects of the toroid. In practice, the external resistive damping completely dominates the damping due to toroid core losses.

The transfer function of the output voltage is given by

$$e_0(s) = \frac{I(s)}{Y(s)} = I(s) \cdot \frac{sL}{1 + s\frac{L}{R} + s^2 LC}$$
 (1)

Since I(s) =  $\frac{I_b}{N} \frac{1}{s} (1 - e^{-sT})$ , where T is the pulse duration, then

$$e_0(s) = \frac{I_b}{NC} \left(1 - e^{-sT}\right) \frac{1}{\left(s^2 + \frac{s}{RC} + \frac{1}{LC}\right)}$$
 (2)

$$e_0(s) = \frac{I_b}{NC} (1 - e^{-sT}) \frac{1}{(s - s_1)(s - s_2)}$$
 (3)

For 
$$\left(\frac{1}{2RC}\right)^2 - \frac{1}{LC} < 0$$
, the roots are  $s_{1,2} = \alpha \pm j\omega_0$ , where

$$\alpha = -\frac{1}{2RC}$$
 and  $\omega_0 = \frac{1}{\sqrt{LC}} \sqrt{1 - \frac{LC}{(2RC)^2}}$  (4)

Substituting and taking the inverse Laplace yields

$$\mathbf{e}_{0}(t) = \frac{\mathbf{I}_{b}}{\mathbf{NC}} \frac{1}{\omega_{0}} e^{-t/2\mathbf{RC}} \left\{ \sin \omega_{0} t - e^{T/2\mathbf{RC}} \sin \omega_{0} (t - T) \right\}$$
(5)

which is valid for  $t \geq T$ .

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Expanding,

$$e_{0}(t) = \frac{I_{b}}{NC} \frac{1}{\omega_{0}} e^{-t/2RC} \left\{ \sin \omega_{0} t - e^{T/2RC} \sin \omega_{0} t \cos \omega_{0} T + e^{T/2RC} \cos \omega_{0} t \sin \omega_{0} T \right\}$$

$$(6)$$

If we select  $\omega_0$  so that  $\omega_0 T \ll \pi$ , then

$$\cos \omega_0 T \approx 1$$
,  $\sin \omega_0 T \approx \omega_0 T$ , (7)

and  $e_0(t)$  becomes

$$\mathbf{e}_{0}(t) = \frac{\mathbf{I}_{b}}{\mathbf{NC}} \frac{1}{\omega_{0}} e^{-t/2\mathbf{RC}} \left\{ \sin \omega_{0} t \left( 1 - e^{T/2\mathbf{RC}} \right) + \omega_{0} T e^{T/2\mathbf{RC}} \cos \omega_{0} t \right\}$$
(8)

If we sample  $e_0(t)$  at  $\omega_0 t = \pi$ ,

$$\mathbf{e}_{0}\left(\frac{\pi}{\omega_{0}}\right) = -\frac{\mathbf{I}_{b}}{\mathbf{NC}} \cdot \frac{1}{\omega_{0}} \quad \omega_{0} \mathbf{T} \quad \mathbf{e}^{-\pi/\omega_{0}^{2}\mathbf{RC}} \quad \mathbf{T}/2\mathbf{RC} \quad \mathbf{e}$$
(9)

$$= -\frac{q_1}{NC} e^{-\pi/\omega_0 2RC} e^{T/2RC}$$
(10)

where  $q_1 = I_b T$  = beam pulse charge. Thus, for the assumption of  $T \rightarrow 0$ , the voltage at  $\omega_0 t = \pi$  is proportional to the pulse charge  $q_1$ . The location of the maxima for finite T and for  $R \rightarrow \infty$  can be determined from Eq. (5) by differentiating with respect to t, and setting equal to zero:

$$\cos \omega_0 t = \cos \omega_0 (t - T)$$

$$t = \frac{\pi}{\omega_0} + \frac{T}{2} \quad \text{for the first peak}$$
(11)

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Thus, for T finite; the maximum is shifted in time by an amount proportional to half the pulse width, which corresponds to the shift of the centroid of the rectangular pulse.

#### C. Resonant Frequency

For the case of zero damping, i.e.,  $R \rightarrow \infty$ , the measurement accuracy obtained when sampling at  $\omega_0 t = \pi$  depends upon the validity of the assumption that  $\sin \omega_0 T \approx \omega_0 T$  [see Eq. (7)]. The accuracy will be  $\leq 0.1$  percent if we restrict  $\omega_0 T \leq 4.5^{\circ}$ ; thus we observe the following restrictions for  $T_{max} = 2 \mu \text{sec}$ :

$$\omega_0 T \le 4.5^{\circ} \times \frac{\pi}{180^{\circ}}$$
 radians  
 $f_0 \le \frac{4.5^{\circ}}{360^{\circ}T} = 6.25 \text{ kHz}$  (12)

#### D. Damping Error

Circuit damping due to R, which represents the combined effects of core losses and external resistive loading, contributes the largest error to the measurement. Resistive damping is necessary to prevent the tail of the ringing signal of one beam pulse from affecting the initial amplitude of the next; thus, damping to  $\ll 0.1$  percent must be accomplished in the minimum interpulse period of 2.78 msec. On the other hand, from Eq. (10), the time constant  $\tau = 2\text{RC}$  should be made as long as possible consistent with the above restriction, because the error, or change, in the peak voltage is  $\left(e^{T/2\text{RC}} - 1\right) \approx T/2\text{RC}$ .

#### E. Circuit Constants

The final determination of circuit constants involves such factors as the relation of R to the preamplifier noise figure, the required physical geometry of the toroid itself, and the desire to standardize the toroid design so that it can be also used as an intensity monitor. For the existing system, the following nominal

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values were chosen:

 $f_0 = 5.25 \text{ kHz}$  L = 28 mH  $C = .033 \mu \text{F}$  R = 5 K ohms $\tau = 2\text{RC} = 0.33 \text{ msec}$ 

The toroid <sup>7</sup> consists of a core 3" i.d. by 6" o.d. by 2" long, wound with 48 turns. Hence, N = 48 and from Eq. 10 we define a sensitivity as follows:

$$S = \frac{V_p}{q_1} = \frac{1}{NC} e^{-\pi/\omega_0^2 RC} e^{T/2RC}$$

where  $V_n$  is the voltage at the second peak.

$$S = \frac{0.57}{(48)(.033)} \cdot 10^6 = 0.36 \times 10^6 \text{ volts/coulomb}$$
(13)

Thus, the signal for a maximum beam of 50 mA peak,  $2 \mu \text{sec}$  duration ( $10^{-7}$  coulomb) will be 36 mV at the sampling point.

For the above circuit constants, crosstalk errors are < .02 percent.

#### F. Optimum Sampling Point

The error due to damping is best visualized as a decrease in the peak amplitude for a widening pulse as the peak slides down the envelope of the damping curve (see Fig. 2). This error would be unimportant if T were a fixed constant; however, this is not generally true and some form of compensation is necessary.

Fortunately, a simple mechanism exists for compensating this error. It is apparent from Fig. 2 that if the sampling point is selected to be just over the first peak, then the shift caused by a widening pulse will show an increase in the sampled value, tending to compensate the decrease due to damping. The optimum

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sampling point, then, is the crossover of the minimally and maximally shifted waveforms, where the amplitude is the same before and after shifting (Fig. 2). This point is determined by matching the slope of the damping factor,  $e^{-t/2RC}$ , to the slope of the cosine wave just beyond the peak. From the above analysis, the optimum point lies  $\approx 5^{\circ}$  beyond the peak of the minimum (zero) width beam pulse, and the maximum theoretical error due to width change is reduced to  $\leq .02$  percent.

#### **III.** SYSTEM DESCRIPTION

#### A. General

The system which has been designed and constructed based on the resonant toroid principle is described in this section.

A block diagram of the system and associated timing of a complete cycle are shown in Figs. 3 and 4 respectively. The operation of the system is described for a single beam pulse. This cycle takes  $360 \ \mu sec$  and is repeated for each beam pulse up to the maximum rate of  $360 \ pps$ . Normally, the system is run at  $360 \ pps$  for optimum noise averaging.

The passage of a beam pulse through the toroid excites the toroid-capacitor resonant circuit. After suitable preamplification the signal is transmitted several hundred feet to the Counting Room where it is amplified, sampled at the optimum time, and held long enough to be digitized in an analog-to-digital converter. The resulting digital data is displayed to furnish pulse charge information, and added to a bidirectional digital accumulator which totalizes the pulse charge and averages the system noise. Digital displays driven by the accumulator and pulse counter continuously display total charge and total beam pulse count. This data is also sent to an SDS 9300 on-line computer.

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Other parts of the system include a digital control system which provides the various timing and control pulses for the analog-to-digital converter, accumulator, and pulse counter; a toroid temperature control system; and a calibration system.

The system is packaged in several different chassis as shown in the block diagram, including the toroid, preamplifier, amplifier and timing, analog-todigital converter, digital accumulator, control-display panel, and power supply chassis. Solid state circuitry for the preamplifier and the amplifier and timing chassis was developed at SLAC; digital circuits in the digital accumulator and digital control system utilize standard commercial digital modules<sup>\*</sup>. Photographs of several of the chassis are shown in Figs. 5 through 9.

#### B. Analog Section

Figure 10 is a block diagram of the analog portion of the system; Fig. 11 shows the important waveforms. The operation is as follows: The toroid resonant signal is amplified by a gain of 100 preamplifier, located close to the toroid, and sent through a balanced shielded cable to the amplifier and timing chassis located in the Counting Room. A reversing switch is provided for e<sup>+</sup> measurement.

The signal next passes through three identical gain-switched stages, each having selectable gains of 1, 3 or 10, and a gain accuracy of  $\sim .02$  percent. The gain is selected to bring the signal to a level between 1 and 10 volts.

At the appropriate time as determined by calibration, the sample-and-hold is given a 5  $\mu$ sec long sample pulse, the trailing edge of which determines the sample point. Figure 11 shows that the sample pulse delay, measured from the delayed trigger, is composed of a sample delay plus an auxiliary delay; the sample delay represents the time from the beam pulse to the peak of the resonant signal,

Standard C and H series, manufactured by Scientific Data Systems, Santa Monica, California

while the auxiliary delay represents the additional time to the optimum sampling point. Both delays are controlled from a single front-panel adjustment, the desired ratio of sampling delay to auxiliary delay having been previously determined by calculation. All the delays illustrated in Fig. 11 are generated by a cascade of conventional one-shots; the one-shots which determine the sample point are housed in a  $40^{\circ}$  C proportionally-controlled oven for added stability.

The sampled value is held for a duration of 1.5 msec, during which time the digital operations take place. At the end of this period, a 1 msec clamp signal restores the sample-and-hold to its initial state and the system is ready for the next beam pulse.

The sample-and-hold circuit has noise and dc offsets of the order of  $\pm 1 \text{ mV}$ , and a specified linearity of  $\sim .02$  percent. An adjustable trim is provided to balance the dc offset below  $\pm 1 \text{ mV}$ .

The output of the sample-and-hold passes through a gain control potentiometer located in the Control Panel, through a chopper stabilized operational amplifier\* buffer, and then to the input of the analog-to-digital converter.

Several other features incorporated in the actual system are described below. First, the toroid itself is provided with a proportionally-controlled heating coil around the Faraday shield, which is in close thermal contact with the ferrite, in order to insure long-term stability of the resonant frequency. The entire assembly is normally in vacuum, so that once the shield is heated, a trival amount of power is required to sustain the temperature. Second, reference voltages of + 5, - 5 and 0 volts are provided which can be switched into the final buffer to check the proper operation of the buffer-ADC combination. The voltages are derived from temperature stabilized reference diodes. The final item in the analog section is the calibration system, which is described more fully in Section IV.

Fairchild Model A006

### C. Analog-to-Digital Converter

The analog-to-digital converter is a commercial unit<sup>\*</sup> of the successive approximation type with a total cycle time of 90  $\mu$ sec and a specified accuracy of  $\pm$  .01 percent of  $\pm$  10 volts full scale,  $\pm$  1/2 least significant bit. The output data format is 4 decimal digits plus sign, coded in 1-2-4-8 BCD, with negative numbers represented in 10's complement form. This coding is used throughout the digital system for compatibility with decimal displays and to eliminate the need for a BCD subtractor in the accumulator. The analog-to-digital converter requires a "convert" pulse to initiate its cycle, and supplies an "end of conversion" pulse when the cycle is complete. The converter runs continuously at 360 pps.

#### D. Digital Accumulator

The design of the digital accumulator is based on the decade adder principle.<sup>13</sup> One decade adder is employed and the 12 decades share the adder sequentially.

A block diagram of the digital accumulator is shown in Fig. 12. The operation for a normal add cycle is described as follows: An add command (end of conversion pulse) is received from the analog-to-digital converter. After a delay of 18  $\mu$ sec to allow the converter data lines to settle, the control system starts the add cycle. Two clocks are generated — the first, running at 1 MHz, clocks the 48-bit shift register containing the total charge data in BCD; the second, running at 1/4 the rate (250 kHz) is used for decade operations.

The first 250 kHz clock pulse, which coincides with the first 1 MHz clock pulse, transfers four bits (least significant decade) from the shift register into the 4-bit buffer, and the input data multiplexer selects the least significant decade from the analog-to-digital converter. The addition is performed in the decade adder logic and the results are parallel-transferred into the 4-bit shift register,

Model AD21-17 manufactured by Scientific Data Systems, Santa Monica, California. Output buffer amplifiers were added for greater drive.

from which the data is subsequently clocked at 1 MHz into the most significant end of the 48-bit shift register. This operation is repeated for the next 3 decades of the analog-to-digital converter. The addition procedure for the remaining 8 decades of the 48-bit shift register is the same except that the data input (from the multiplexer) to the decade adder is zero for positive input data from the converter, and nine for the negative data, these values being necessary to perform 10's complement arithmetic.

A counter in the control system determines when the addition cycle is complete, terminates the clock pulses and sends a pulse to the 28-bit BCD counter (total pulse counter) which then increments by one if the data was from a valid beam pulse, rather than from sampled noise.

At each transfer into the 4-bit buffer from the shift register, the data is examined for an invalid BCD code. The decade data from the analog-to-digital converter is similarly examined. Upon detection of such an error the associated light is illuminated, remaining in this state until a reset is initiated. In addition, a power error indicator is illuminated if there is a temporary power outage. The digital accumulator can be operated in a single clock mode for maintenance purposes.

#### IV. CALIBRATION SYSTEM

#### A. Calibrator Circuit

Figure 13 shows the circuit which sends a simulated beam of precisely  $10^{-8}$ ,  $10^{-9}$  or  $10^{-10}$  coulombs through the calibrate turn of the toroid.

The operation of the pulser is straightforward: Initially the capacitor  $C_0$  is charged to a known voltage  $V_0$ , where  $C_0$  and  $V_0$  are both known to ~.05 percent. When a delayed trigger is applied, a one-shot drives the transistor switch into saturation, thus connecting the charged capacitor across the output cable, which is matched into 50 ohms at the receiving end. In the simplest analysis, all of the charge ( $C_0V_0$ ) must flow through the calibrate winding, and it is necessary only to damp the circuit so that the discharge is complete in the shortest possible time. In the circuit shown,  $C_0$  and  $V_0$  are a nominal 1000 pF and 10 V respectively, so that  $Q_0 = 10^{-8}$  coulomb, and the duration of the pulse is approximately 0.5  $\mu$ sec. The matched attenuator near the toroid provides additional calibration charges of  $10^{-9}$  and  $10^{-10}$  coulombs; the attenuator steps are accurate to  $\pm 0.1\%$ .

The absolute accuracy of the charge is subject to any pulse noise generated by the transistor switch; this effect has been measured to be <.025 percent of the standard  $10^{-8}$  coulomb charge. Thus, the  $10^{-8}$  coulomb pulse is conservatively estimated to be accurate to better than  $\pm 0.1\%$ .

Once triggered, the transistor switch must be held in saturation until after the resonant signal is sampled, which occurs approximately 100  $\mu$ sec after passage of the beam pulse. If the switch is released before this time, the capacitor recharging current flowing through the calibrate winding will cause significant errors.

#### B. System Operation

Calibration of the system is described below with reference to the Analog Timing Diagram of Fig. 11. Calibration entails first, location of the optimum sampling point; second, adjustment of the gain; and third, proper adjustment of the trigger delay to assure that the simulated beam arrives at the same time as the actual beam.

The system is calibrated in the following way: First a button is pushed which eliminates the auxiliary delay, and the sample pulse delay is adjusted to the peak of the resonant signal, as observed on the ADC digital display. Releasing the

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button shifts the sample pulse to the optimum sampling point. The gain is now adjusted so that the ADC indicates the exact value of calibration charge. Several runs are then made to determine if finer adjustment is required.

Finally, the trigger delay is adjusted to the leading edge of the beam pulse. This control requires adjusting only when the instrument is installed at a new location, since the trigger-to-beam pulse delay is a constant for a given location.

#### V. RESULTS

The three major criteria of performance which were studied were, (1) overall system stability and accuracy, (2) sensitivity, or noise limitations, and (3) comparison with a Faraday cup. The results are summarized in Tables I and II.

A. Calibration Stability

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Table I, column 5, shows, for the indicated value of gain and calibrate charge, the gain-normalized ratios over the entire range of the instrument. Each average and standard deviation is obtained from 8 consecutive runs of  $10^4$  samples each (approximately 30 seconds). Column 6 represents a noise measurement at each setting, with no calibration signal present, also determined from 8 runs of  $10^4$  samples each, and converted to an equivalent noise current. Column 7 shows the equivalent noise current as a percentage of simulated beam current for each measurement.

Table I also shows the reduction of the random component of noise for runs of  $10^5$  instead of  $10^4$  samples (5 minutes instead of 30 seconds), and the system stability over a 7-hour period.

From the first row of the table, the short term repeatability is a few parts in  $10^5$ ; while from the last section, the long term stability of the entire system is seen to be of the order of 1 part in  $10^4$  over a 7-hour period.

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All the normalized readings in column 5 are within  $\pm$  0.1 percent except for the 10<sup>1</sup> and 3 × 10<sup>1</sup> gain settings. These readings, which are slightly more than 0.1 percent low, are most likely caused by an error in the 10<sup>-9</sup> coulomb step of the calibrate attenuator.

From column 7, it is seen that for runs of  $10^4$  pulses, drift errors are less than  $\pm 0.1$  percent from an average current of 36 nA to the maximum average beam current of 36  $\mu$ A (50 mA, 2  $\mu$ sec, 360 pps), a range of 1000:1.

Column 7 shows also that on the highest gains of  $3 \times 10^2$  and  $10^3$ , the drift component of noise increases; however, for the calibration runs shown, these drifts do not appear to reflect as errors in the data. Since the calibrator operates at a constant 360 pps, it appears that the noise averaging limitations near zero signal do not appear at higher levels. In reality, however, the beam rate is usually less than 360 pps; thus the drifts must be considered to be the present limit of measurement accuracy for low-rate beams. These effects, and the possibilities of drift correction, are the subject of further study.

The second section of Table I shows that the random component of drift decreases approximately as  $\sqrt{N}$  for longer runs.

#### B. Faraday Cup Comparisons

Table II shows the results of comparing the resonant toroid system with the SLAC Faraday Cup. <sup>14</sup> All of the data presented was collected during the course of normal experiments, which in general were not specifically designed for optimum testing of the two monitors. The toroid was located approximately 50 feet ahead of the cup, and the presence of a certain amount of material, including an  $LH_2$  target and/or an air path, contributes to uncertainties in the measurements. Furthermore, in the data reported in items 1, 2, and 3, taken over a 1-week continuous experiment, the self calibration of the toroid was not recorded

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sufficiently often to make corrections. Hence, these data primarily illustrate the long-term stability of the toroid system for a variety of beam currents, energies and target conditions. In spite of these limitations, the toroid and Faraday cup agreed to approximately  $0.7 \pm 0.3$  percent over the 1-week run.

The data presented in item 4 was made with a new amplifier and timing chassis in the system. This system was calibrated prior to the run, and the timing section in particular was set up more carefully. Furthermore, calibration data from the toroid calibrator was taken during the 3-day run, so corrections could be applied. The results show a toroid-to-Faraday cup ratio of  $-0.22 \pm .06$  percent.

The final test, item 5, was a measurement of the toroid response to a 10 MHz RF chopped beam, which consists of single bunches of electrons spaced by 50 nsec. The Faraday cup was used to normalize the ratio of toroid [normal beam] to toroid [chopped beam]. The agreement of the measurements to  $.08 \pm .03$  percent demonstrates that the toroid response is not sensitive to details of the beam structure, but only to the total beam charge.

#### VI. CONCLUSION

The resonant toroid charge monitor described appears capable of  $\pm 0.1$  percent accuracy over the range of average currents of 36  $\mu$ A to 36 nA, for runs of  $10^4$  pulses. At levels below 36 nA, it appears possible to apply drift corrections to extend this range; however, further study of these effects, in relation to different beam rates, is necessary. The random component of noise is observed to reduce as expected for longer runs.

The toroid versus Faraday cup data verifies the stability of the system over a variety of practical operating conditions. In one particular 3-day experiment, where calibration data was available, the toroid/cup ratio was -  $0.22 \pm .06$  percent.

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Further experiments are planned to compare the toroid and Faraday cup under more closely controlled conditions.

The RF chopped beam test verifies that the toroid response is independent of the detailed structure of the beam, to within the measurement accuracy of the system.

At the present time, factors affecting the optimum sampling point are being examined more critically. A recent computer analysis indicates that the method described in II(F) for determining the optimum sampling point may be improved, resulting in a better absolute calibration. Further comparisons between toroid and Faraday cup are planned in order to evaluate the effects of such factors on the absolute calibration.

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## TABLE I

# CALIBRATION AND NOISE MEASUREMENTS INITIAL CALIBRATION AT GAIN $10^{\circ}$ , Q = $10^{-8}$ COUL.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Gain	Cal. Chg. Coul/Pulse	Eq. Beam Current	No.Runs (N = 10 <sup>4</sup> )	Normalized Rdgs. $\overline{\mathbf{x}} \pm \boldsymbol{\sigma}$	Equivalent Noise Current $\overline{\mathbf{x}} \pm \sigma$	Noise % of Rdg. $\overline{x} \pm \sigma$
10 <sup>0</sup>	10 <sup>-8</sup>	3.6 µA	8	$1.00004 \pm .00002$	+148. ± 30.6 pA	.004 ± .0008%
3 ·10 <sup>0</sup>	10 <sup>-8</sup>	3.6 µA		1.00032 ±.00002	+ 141. ± 20.9 pA	$.004 \pm .0006\%$
10 <sup>1</sup>	10 <sup>-9</sup>	0.36 μΑ		$0.99864 \pm .00004$	+ 79 ± 15.7 pA	$.022 \pm .004\%$
$3 \cdot 10^{1}$	10 <sup>-9</sup>	0.36 μΑ		0.99896 ±.00004	+ 108 ± 13.1 pA	$.030 \pm .004\%$
10 <sup>2</sup>	10 <sup>-10</sup>	36 nA		$1.00049 \pm .00022$	+ 18.3 ± 12.3 pA	$.051 \pm .034\%$
3·10 <sup>2</sup>	10 <sup>-10</sup>	36 nA		0.99900 ±.00034	+ 67.3 ± 12.5 pA	.187 ± .035%
10 <sup>3</sup>	$\frac{10^{-10}}{3}^{*}$	10 nA*		1.0005 <sup>▲</sup> ± .001	+ 72.0 ± 13.4 pA	$.72 \pm .13\%$

\*Approximate

•From comparison with  $3 \cdot 10^2$  scale

Gain	No. Runs	Eq. Noise $N = 10^4$	Eq. Noise $N = 10^5$
10 <sup>3</sup>	8	63.3 ± 15.1 pA	63.0±3.8 pA

Gain	Cal. Chg.	No. Runs $(N = 10^4)$	Time	Avg. Norm. Rdg. Uncorrected
10 <sup>0</sup>	10 <sup>-8</sup>	8	0 hrs	1.00004
		4	+ 4	1.00014
ļļ		4	+ 7	1.00013

## TABLE II

# COMPARISON WITH SLAC FARADAY CUP

	Measurement	$\frac{[\text{Toroid/Faraday Cup}]^*}{\bar{x} \pm \sigma}$
1.	Data from 4 - 11 October 67 Average of 15 independent readings, target out; various energies;gain < 10 <sup>2</sup> for all readings; toroid calibration data not available.	1.0065 ± .0030
2.	Same data as in (1); first 2 readings, made during setup, deleted	1.0076 ± .0003
3	Data from 4 - 11 October 67 Average of 19 independent readings, $LH_2$ target in; various amounts $LH_2$ ; various energies; gain < $10^2$ for all readings; toroid calibration data not available.	$1.0073 \pm .0026$
4	<ul> <li>Data from 14 - 16 December 67</li> <li>Average of 7 independent readings, LH<sub>2</sub></li> <li>target both in and out during readings;</li> <li>various energies; toroid calibration corrections made.</li> </ul>	0.9978 ± .0006
5	. Chopped Beam Test	$Toroid/Cup \left[ \frac{Normal Beam}{Chopped Beam} \right]$
	Data from 20 February 68 Normal Beam $\cong 6.0 \times 10^{-8}$ A 10 MHz Chopped $\cong 6.5 \times 10^{-8}$ A 60 PPS Beam Gain = 10 Run Sequence: 1 - Normal 2,3,4,5 - Chopped 6,7,8 - Normal $\Delta T = 100$ sec. = Duration each run	0.9992 ± .0003

\*Toroid  $\approx 50'$  upstream of Faraday cup for all data.

#### LIST OF FIGURES

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- 11. Analog timing diagram.
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- 13. Calibrator circuit.



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FIG. I-TOROID AND EQUIVALENT CIRCUIT



FIG. 2-OPTIMUM SAMPLING POINT



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FIG. 3-SYSTEM BLOCK DIAGRAM

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# FIG.4-SYSTEM TIMING DIAGRAM



# FIG. 5 - ASSEMBLED TORID



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FIG. 6 - PREAMPLIFIER

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FIG. 7 - AMPLIFIER AND TIMING CHASSIS



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FIG. 8 - CONTROL PANEL AND DISPLAYS

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FIG. 9-CONTROL PANEL - REAR VIEW



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FIG. 10-ANALOG SECTION BLOCK DIAGRAM

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FIG.11-ANALOG TIMING DIAGRAM

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FIG. 12 - DIGITAL ACCUMULATOR BLOCK DIAGRAM

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FIG. 13-CALIBRATOR CIRCUIT

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