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TOROIDAL CHARGE MONITORING SYSTEMS*

by

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I. INTRODUCTION

Toroidal charge monitors are in use at SLAC in two main areas: for measuring the primary electron beam charge at 30 stations along the length of the 2-mile accelerator; and for precise measurement of primary electron beam charge in the experimental areas. The nominal required measurement accuracy in the machine area and in certain target areas is ± 1%. In the End Station A area, however, where a wide variety of precision scattering experiments are performed using the 1.6, 8.0 and 20 GeV spectrometers, a primary beam measurement accuracy of ± 0.1% is required. The differing requirements have led to essentially 3 different measuring systems.

In the following paragraphs, the basic features of these systems will be briefly described, as well as a new system being developed for the Storage Ring (SPEAR). The general applicability of toroids to the LAMPF beam will be discussed.

II. PRIMARY BEAM MONITORS FOR THE ACCELERATOR

The toroidal charge monitors used along the machine use a small 1 1/2" id × 3" od × 2" long toroid with 24 turns, terminated in a 50 Ω resistance to obtain a waveform proportional to $i_b(t)$. Integration is performed, after ac amplification, by gating the signal into a 2-stage RC type of integrator, and then sampling and buffering the peak of the integrated waveshape. The nominal accuracy obtained is ± 1%. Gating spikes, pulse droop, and timing drifts all are bothersome, and fairly frequent calibrations are necessary. The system is described in detail in Reference 1. It should be noted here that the method of integration was essentially dictated by the need to use the same toroid both as an intensity monitor and as a charge monitor.

III. PRECISION MONITORS FOR EXPERIMENTAL AREAS

A more recent development has been the system used in End Station A, first installed in 1966. A second identical system was installed in mid-1968. In these systems, the toroid operates in a resonant mode such that the integral of the beam current is obtained directly at the toroid output. This signal is amplified, sampled, and converted to digital form. The accuracy obtained is ± 0.1%. The system is described in detail in Reference 2. An error analysis is given in Reference 3.

A variation of this system is used in the End Station B area. In this application, very high current primary beams are brought into the B Target Room, where 3 main secondary beams (muons, pions and kaons) are produced. In view of the high primary currents, a measurement accuracy of ± 1% is sufficient; hence for this application the End Station A system was modified to include a simpler A to D and a simpler readout scheme using a conventional scaler. Readout of the data at a remote station is also simpler.

IV. RESONANT TOROID SYSTEM

A. Theory

The resonant toroid equivalent circuit is shown in Figure 1. Here, the toroid of N turns is loaded with a capacitor to create a resonant circuit, which is damped by the preamplifier input resistance R.

The resultant output waveform for a rectangular input pulse of width T is

$$e_0(t) = \frac{I_b}{NC} \cdot \frac{1}{\omega_0} \cdot e^{-t/2RC} \left\{ \sin \omega_0 t (1 - e^{T/2RC}) + \omega_0 T e^{T/2RC} \cos \omega_0 t \right\} .$$

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Assume

$$\left.\begin{array}{l} N = 300 \\ L = 1080\ \text{mH} \\ C = 6.55\ \mu\text{F} \end{array}\right\} f_0 = 60\ \text{Hz}$$

For a maximum beam of 100 μA, 500 μsec long, the maximum undamped signal amplitude is

$$\frac{Q}{NC} = \frac{5\times 10^{-8}}{300\times 6.55\times 10^{-6}} = 25\ \mu\text{v}$$

Thus the signal is about 1000X smaller than in the present system, and although this signal could probably be measured with a noise averaging system to ± 0.1%, the dynamic range would be extremely limited.

VI. MEASURING LONG SPILL BEAMS USING TOROIDS

The resonant system, then, appears very limited for long-spill beams because the large L and C required results in low sensitivity. A more direct approach appears necessary.

One method of detecting a long-spill beam envelope is shown in Figure 5, where the previous toroid equivalent circuit is used. In the first stage, the detected beam current is converted into a voltage of value $i_1(t) \times R_1$. Because R_{in} is essentially equal to R_1/A_1, the decay time-constant L/R_{in} can be made very long.

For example, if

$L = 25$ mH (N = 30 turns on the SLAC toroid)

$R = 10$ K

$A = 10^5$

then $L/R_{in} = \dfrac{25\times 10^{-3} \times 10^5}{10^4} = 250$ msec is the decay time constant. For a beam pulse 0.5 msec long, this time constant is 500X the pulse length; hence an integration accuracy of 0.1% should be achievable. The remainder of Figure 5 shows an ac-coupled clamp arrangement for removing dc offsets which would otherwise disturb the integrator following. Here also, $R_2C_1 \gg T$ in order to minimize pulse droop. Immediately after integration, the signal is sampled and digitized, after which the reset switches are actuated to restore C_1 and C_2 in preparation for the next beam pulse.

As a practical matter, the input stage in this scheme probably requires some additional dc stabilization because in a voltage sense the amplifier is operating open-loop. Also, the toroid will have to be particularly well shielded against pickup. For low-level signals where pickup is significant, a digital noise averaging scheme would have the usual advantages. In fact, noise averaging in some form appears to be a very worthwhile feature for any toroid charge monitoring scheme.

The first stage of this system has been briefly tested using a Zeltex 804M1 amplifier with a gain of 10^5. Although the time constant achieved was only 60 msec rather than the predicted 250 msec, the principle appears valid.

A system developed by Unser[4] of CERN uses toroids of the feedback type developed by H. G. Hereward to monitor an extremely broad bandwidth of signals. Such a system is being developed at SLAC by R. Scholl for the SPEAR Storage Ring project.

The basic system is shown in Figure 6[4]. In this system, a dc transformer is combined with a fast transformer in a feedback arrangement. Part of the dc transformer is modulated by a low frequency signal; the feedback system detects the second harmonic of this signal and reduces it to zero by generating a current on a separate winding in opposition to the slow envelope of the beam current. Thus a signal appears across the feedback resistor which is directly proportional to $i_b(t)$. The fast beam variations detected in the second toroid similarly appear across this resistor. The accuracy of this system should be of the order of ± 0.1%.

For charge monitoring, the output could be simply integrated as previously suggested. However, since this monitor was essentially designed to view very short as well as very long pulses, it possibly could be simplified considerably for charge monitor applications.

VII. SUMMARY AND CONCLUSION

Toroids present certain difficulties in measuring long-spill beams. The resonant system appears to be inappropriate for such beams because of the reduced sensitivity at low resonant frequencies.

However, using methods such as suggested in Figure 5, or the one developed at CERN, it appears possible to obtain sensitive integration to ± 0.1% over a wide range.

Assume

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Using the SLAC system as a model, toroids should be capable of measuring charge to ± 0.1% down to at least 1 μA peak of the 500 μsec LAMPF beam.

VIII. LIST OF REFERENCES

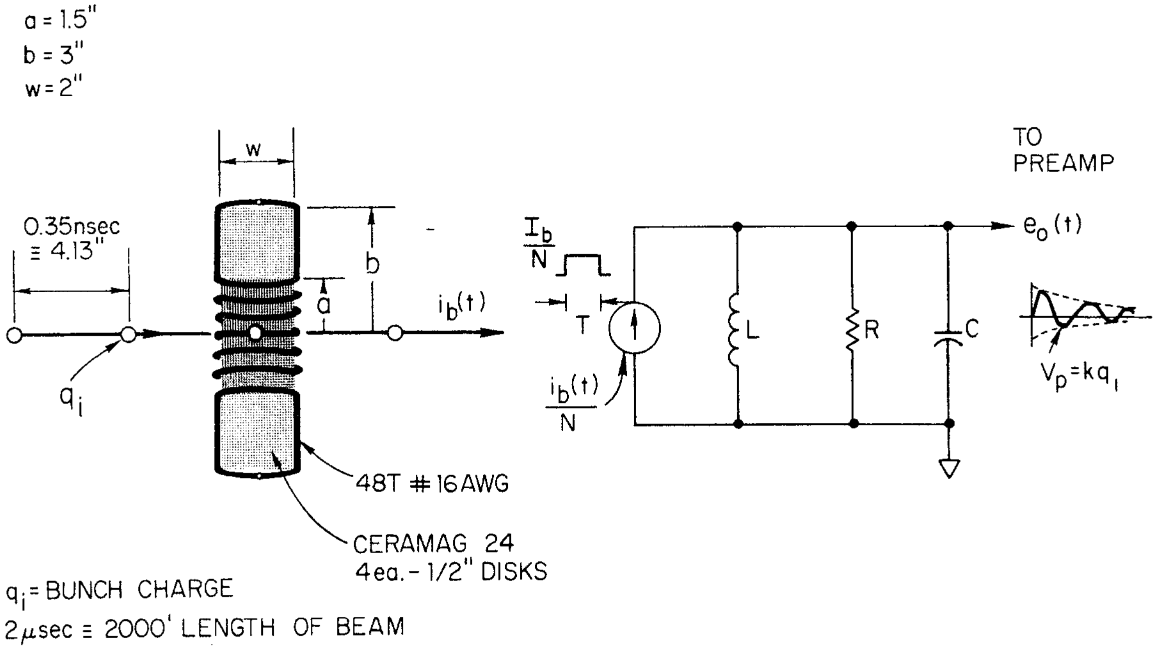
1. "Design of Beam Position and Charge Monitoring Circuits for the Stanford Two-Mile Accelerator", R. S. Larsen, SLAC Report No. 63, May 1966.

2. "A Precision Toroidal Charge Monitor for SLAC", R. S. Larsen and D. Horelick, SLAC PUB-398, Proceedings of the Symposium on Beam Intensity Measurement, Daresbury, 22-26 April 1968, DNPL/R1, pp 260-279.

3. "Digital Computer Error Analysis of a Resonant Toroid Charge Monitor", Dale Horelick and Raymond S. Larsen, SLAC Report No. 100, March 1969.

4. "Beam Current Transformer With DC to 200 MHz Range", K. Unser, Transactions on Nuclear Science NS-16 No. 3, June 1969, pp 934-938.

LIST OF FIGURES



a) GEOMETRY

b) EQUIVALENT CIRCUIT

1006A1

Fig. 1

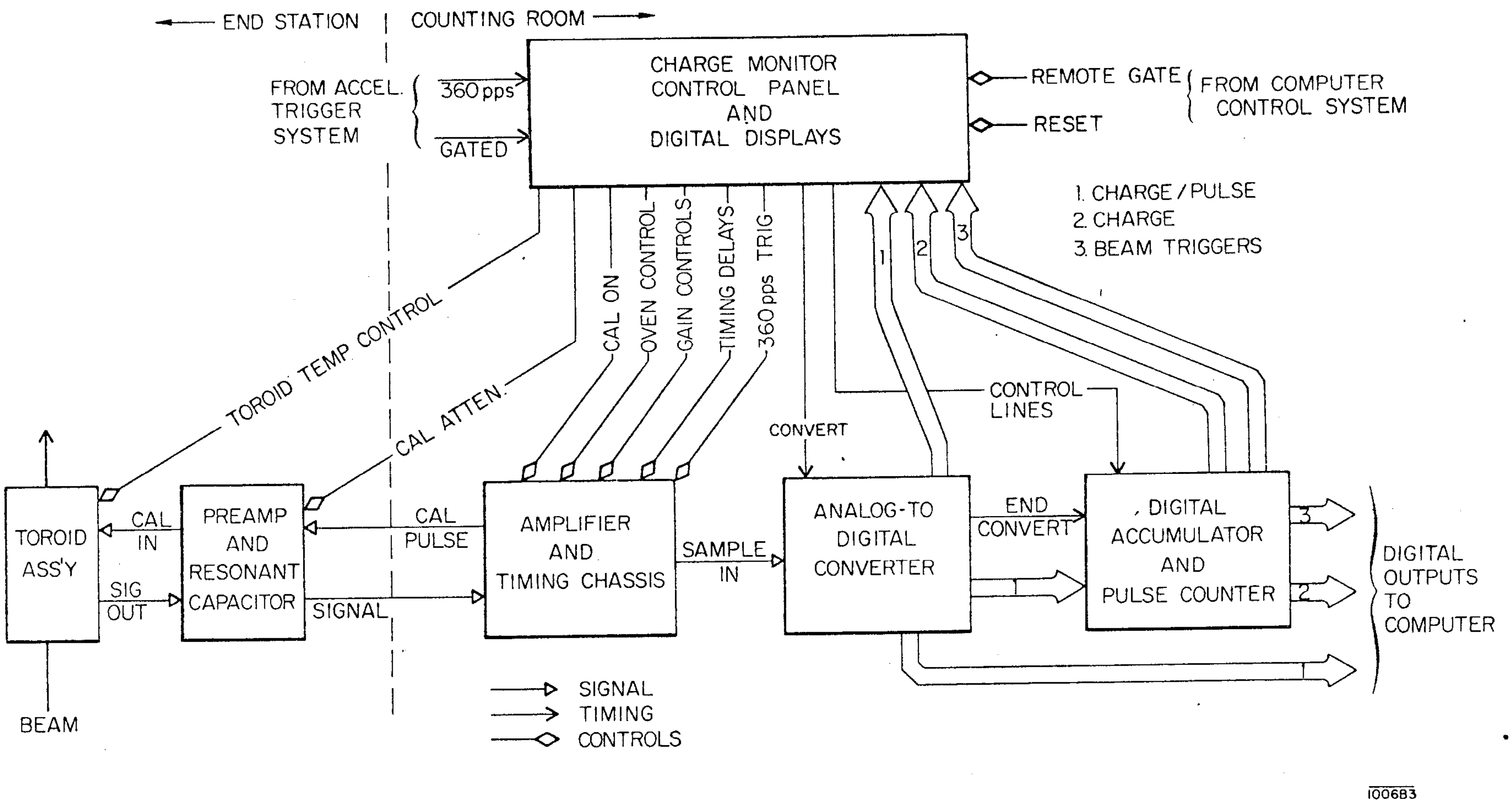

END STATION
COUNTING ROOM
CHARGE MONITOR CONTROL PANEL AND DIGITAL DISPLAYS
FROM ACCEL. TRIGGER SYSTEM
360 pps
GATED
REMOTE GATE
RESET
FROM COMPUTER CONTROL SYSTEM
1. CHARGE / PULSE
2. CHARGE
3. BEAM TRIGGERS
TOROID TEMP CONTROL
CAL ATTEN.
CAL ON
OVEN CONTROL
GAIN CONTROLS
TIMING DELAYS
360 pps TRIG
CONVERT
CONTROL LINES
1
2
3
TOROID ASS'Y
CAL IN
SIG OUT
PREAMP AND RESONANT CAPACITOR
CAL PULSE
SIGNAL
AMPLIFIER AND TIMING CHASSIS
SAMPLE IN
ANALOG-TO DIGITAL CONVERTER
END CONVERT
DIGITAL ACCUMULATOR AND PULSE COUNTER
DIGITAL OUTPUTS TO COMPUTER
BEAM
SIGNAL
TIMING
CONTROLS
100683

Fig. 2

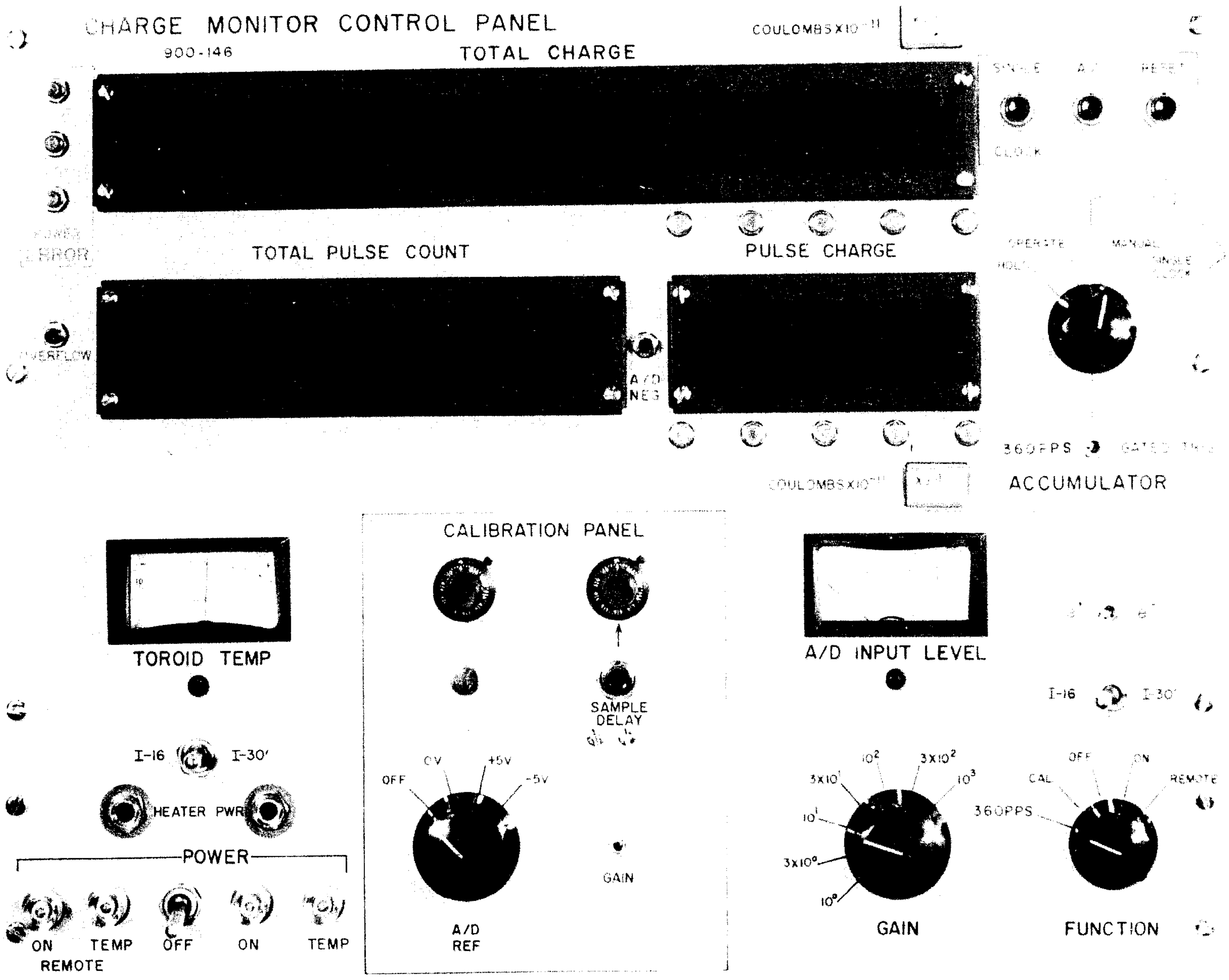


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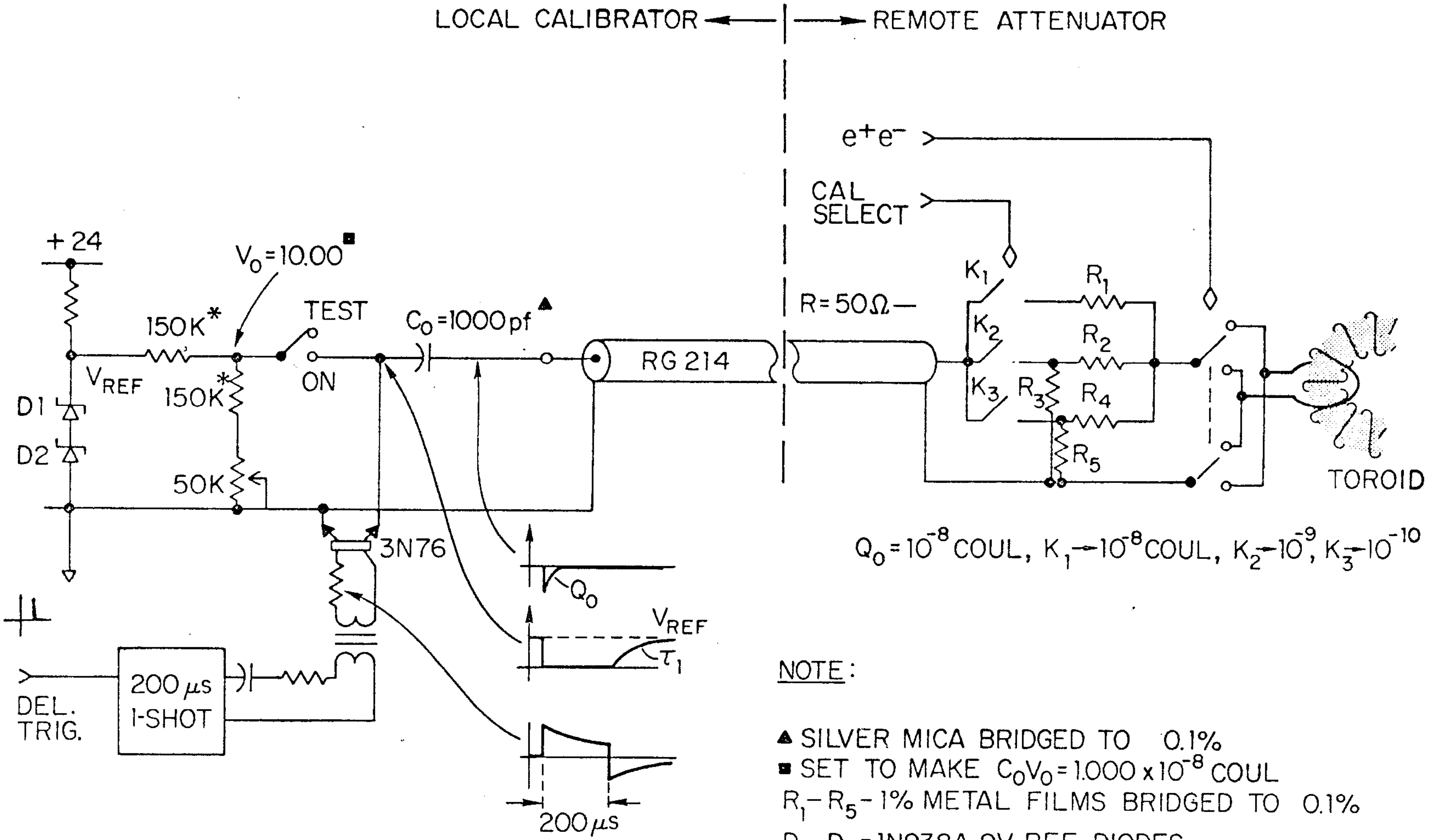
Fig. 3



$Q_0 = 10^{-8}$ COUL, $K_1 \rightarrow 10^{-8}$ COUL, $K_2 \rightarrow 10^{-9}$, $K_3 \rightarrow 10^{-10}$

NOTE:

▲ SILVER MICA BRIDGED TO 0.1%

■ SET TO MAKE $C_0 V_0 = 1.000 \times 10^{-8}$ COUL

$R_1 - R_5$ - 1% METAL FILMS BRIDGED TO 0.1%

$D_1 - D_2$ = 1N938A 9V REF. DIODES

* PRECISION W.W. .02%, ±5ppm/°C

1006A8

Fig. 4

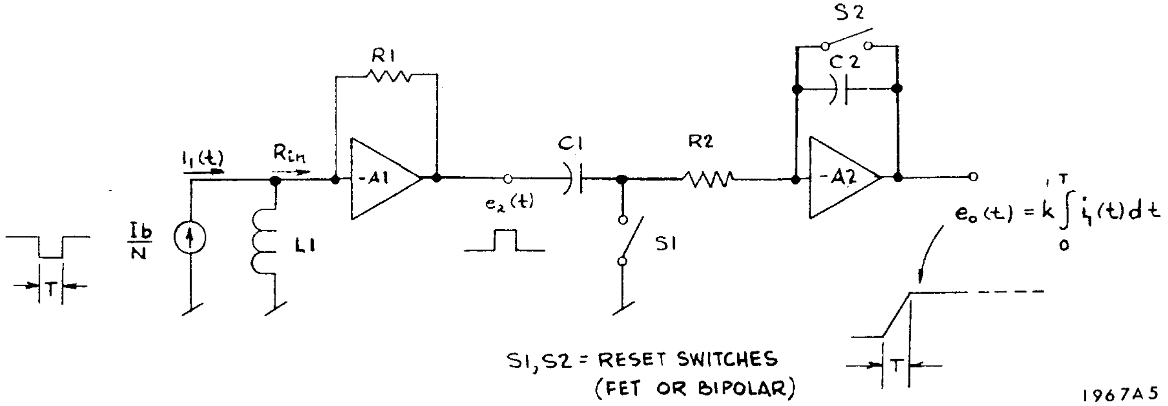
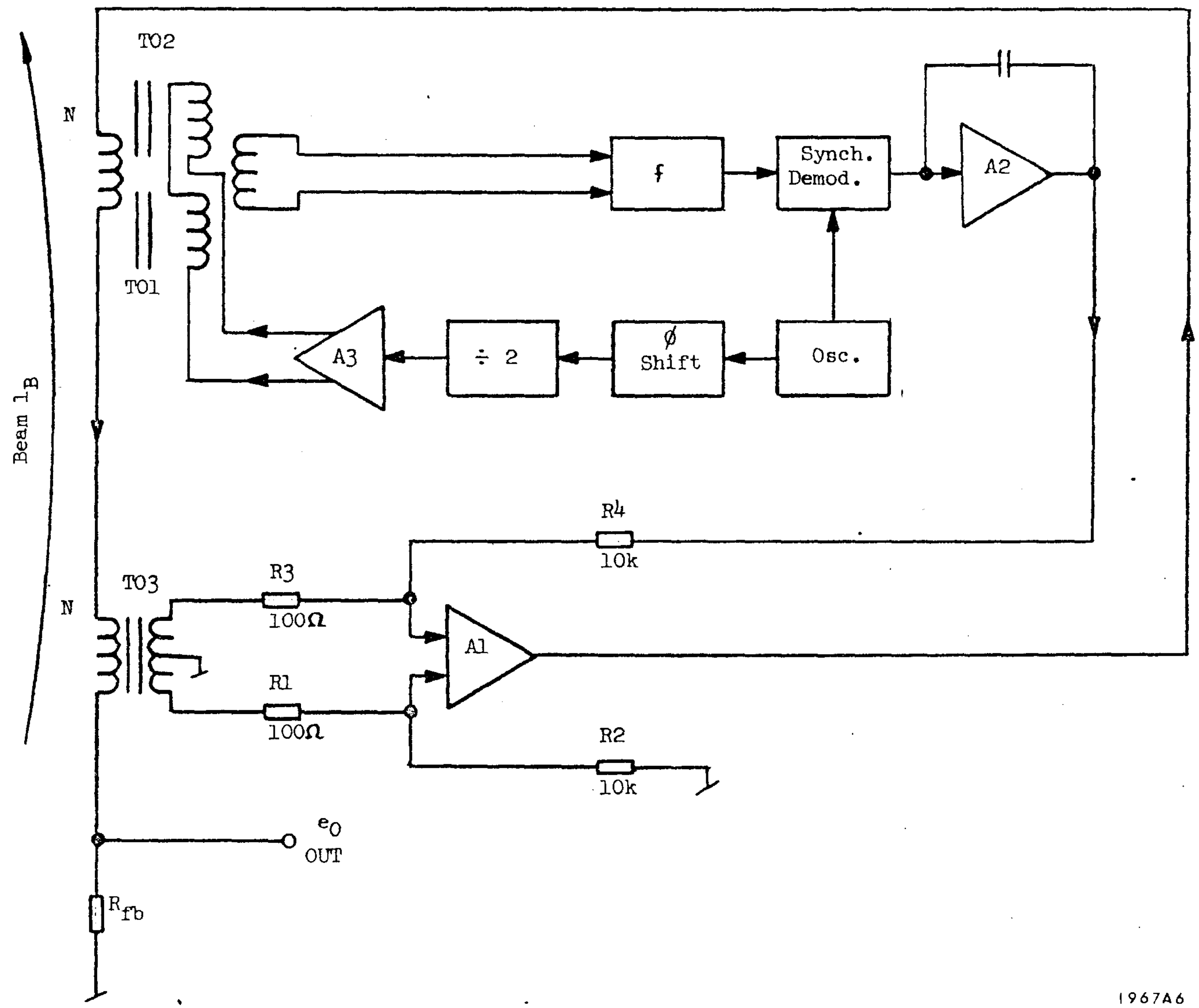

R1
S2
C2
$i_1(t)$
R_{in}
-A1
C1
R2
-A2
$e_2(t)$
$\frac{I_b}{N}$
L1
S1
T
$e_o(t) = k\int_0^T i_1(t)\,dt$
S1, S2 = RESET SWITCHES
(FET OR BIPOLAR)
T
1967A5

Fig. 5


T02
N
T01
Beam 1_B
f
Synch.
Demod.
A2
A3
÷ 2
ø
Shift
Osc.
R4
10k
T03
N
R3
100Ω
A1
R1
100Ω
R2
10k
e_0
OUT
R_{fb}

1967A6

Fig. 6