

# Charge calibration of CsI(Tl)/photodiode spectroscopy systems

John Valentine, Valentin Jordanov, David Wehe and Glenn Knoll

Department of Nuclear Engineering, The University of Michigan, Ann Arbor, MI, USA

Received 6 November 1991

A charge calibration method for spectroscopy systems that use inorganic scintillators, photodiodes, and charge-sensitive preamplifiers is presented. The shaped square wave (SSW) method accounts for ballistic deficit when long decay time constants are present. The SSW method is demonstrated for CsI(Tl) and compared to other calibration methods.

## 1. Introduction

The use of charge-sensitive preamplifiers with scintillators has gained considerable popularity in spectroscopy systems, particularly with the evolution of photodiodes (PDs) as viable photodetectors. The excellent spectral matching of silicon PIN PDs and CsI(Tl), which has the largest scintillation yield of known inorganic scintillators, has contributed significantly to the increased interest in these systems. By using charge-sensitive preamplifiers to process signal pulses from PDs the total charge contributing to a pulse can directly be determined. Knowledge of the total charge is needed to determine the absolute scintillation yield and to quantify the contribution of noise to energy resolution. Both of these properties are important when choosing a scintillator and photodetector for a particular application.

For systems with scintillators, photodiodes, and charge-sensitive preamplifiers, the minimum preamplifier output pulse rise time is limited by the decay time constant(s) of the scintillator. To preserve the full amplitude of the preamplifier pulse through the shaping process, it is necessary for any shaping time constants to be long compared to the decay time constant(s) of the scintillator. If the shaping time is not long enough then ballistic deficit will degrade the pulse amplitude. Furthermore, determining the total charge created in a PD by a scintillation event requires calibrating the spectroscopy system from pulse amplitude to charge. Therefore, any significant ballistic deficit must be accounted for by the calibration method to accurately determine total charge. Since CsI(Tl) has a decay time constant on the order of microseconds, ballistic deficit will be a concern when using common

commercially available amplifiers (shaping time constants of no more than 12  $\mu$ s).

## 2. CsI(Tl) scintillation pulses

The temporal distribution of CsI(Tl) scintillation light can be represented approximately as a rising exponential and a sum of two decaying exponentials

$$\frac{d}{dt}N(t) = \frac{N_1}{\tau_1}e^{-t/\tau_1} + \frac{N_2}{\tau_2}e^{-t/\tau_2} - \left[ \frac{N_1 + N_2}{\tau_r} \right]e^{-t/\tau_r}, \quad (1)$$

where  $N_1$  and  $N_2$  are total yields and  $\tau_1$  and  $\tau_2$  are decay time constants for decay modes 1 and 2, respectively, and  $\tau_r$  is the rise time constant. The measured time constants are  $\tau_1 = 800$  ns,  $\tau_2 = 6.0$   $\mu$ s, and  $\tau_r = 40$  ns as shown in fig. 1.

After the scintillation light is converted to electron-hole (e-h) pairs in the PD, the pulse will continue to have the same basic shape, as long as the PD rise time is short compared to the rise time constant. The electron current pulse produced by a scintillation event is:

$$I(t) = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2} - (I_1 + I_2) e^{-t/\tau_r}, \quad (2)$$

and the total charge of the pulse is:

$$Q_{\text{CsI}} = \int_0^{\infty} I(t) dt = I_1\tau_1 + I_2\tau_2 - (I_1 + I_2)\tau_r; \quad (3)$$

then, defining  $Q_1 = I_1\tau_1$  and  $Q_2 = I_2\tau_2$ , eq. (3) simplifies to

$$Q_{\text{CsI}} = Q_1 + Q_2 - \left( \frac{Q_1}{\tau_1} + \frac{Q_2}{\tau_2} \right) \tau_r, \quad (4)$$

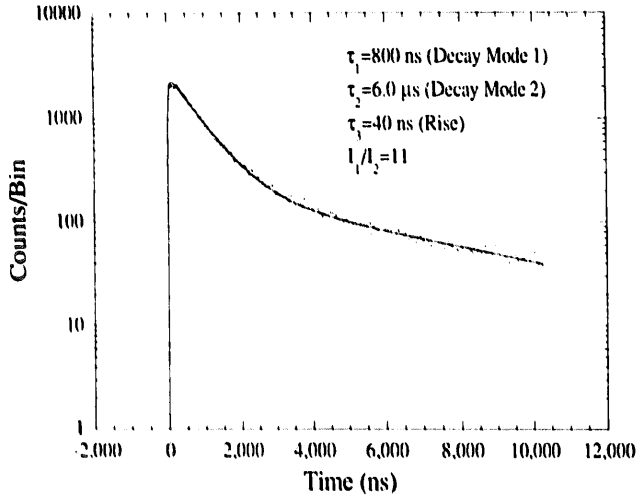


Fig. 1. CsI(Tl) scintillation pulse shape at room temperature and fit for rise and decay time constants. Measured using delayed-coincidence method [2,3].

and eq. (2) becomes

$$I(t) = \frac{Q_1}{\tau_1} e^{-t/\tau_1} + \frac{Q_2}{\tau_2} e^{-t/\tau_2} - \left( \frac{Q_1}{\tau_1} + \frac{Q_2}{\tau_2} \right) e^{-t/\tau_r} \quad (5)$$

When this current pulse is introduced into a charge-sensitive preamplifier, where  $\tau_F = R_F C_F$  is the time constant of the charge integrator, the current pulse integrated over the feedback capacitor,  $C_F$ , yields a voltage pulse with the following time dependence:

$$V_{\text{Preamp}}(t) = \frac{Q_{\text{Csl}}}{C_F} e^{-t/\tau_F} - \frac{Q_1}{C_F} e^{-t/\tau_1} - \frac{Q_2}{C_F} e^{-t/\tau_2} + \left( \frac{Q_1}{\tau_1} + \frac{Q_2}{\tau_2} \right) \frac{\tau_r}{C_F} e^{-t/\tau_r} \quad (6)$$

when  $\tau_F \gg \tau_1, \tau_2, \tau_r$ . For  $\tau_r \ll \tau_1, \tau_2 \ll \tau_F$  the peak voltage is  $V_{\text{Csl}} = Q_{\text{Csl}}/C_F$  [1]. Fig. 2 demonstrates the derived pulse shapes for a CsI(Tl) scintillation pulse. This representation is an idealization of the preamplifier behavior, but the function of actual components is consistent with this idealization.

When these pulses are subsequently shaped in the linear amplifier, some ballistic deficit is unavoidably created due to the large value of  $\tau_2$  (6  $\mu\text{s}$ ). Therefore, the amplitude of the shaped pulse will increase with increasing shaping times ( $\tau_{\text{Amp}}$ ).

### 3. Conventional charge calibration methods

Two methods have been traditionally used for calibration of systems with PDs: observing direct photon interactions in the PD and introducing a square wave

voltage pulse onto the input capacitor,  $C_{\text{Test}}$ , of the preamplifier.

#### 3.1. Direct interactions in PD

The use of direct gamma-ray interactions in a PD has been a widely used charge calibration method. It relies on a full energy event,  $E_\gamma$ , in the PD creating  $Q_{\text{DI}} = E_\gamma/\epsilon$  e-h pairs, where  $\epsilon$  is the average deposited energy necessary to create an e-h pair. Although this method accurately determines the charge created by a direct interaction in the PD, the charge is introduced to the preamplifier in a time frame that is short compared to that characterizing a CsI(Tl) scintillation event. In this case, the preamplifier output pulse rise time is short compared to most shaping times and thus not affected by ballistic deficit. Fig. 3 demonstrates how the ballistic deficit affects direct interaction calibration, where the total charge created in the PD by the direct interaction is assumed to be the same as a CsI(Tl) scintillation event ( $Q_{\text{DI}} = Q_{\text{Csl}}$ ) to illustrate the problem. Furthermore, the shaped calibration pulse amplitude will be nearly constant for all shaping times, while the shaped CsI(Tl) pulse amplitude increases with shaping time.

#### 3.2. Square wave on $C_{\text{Test}}$

Introducing a square wave of amplitude  $V_0$  onto  $C_{\text{Test}}$  through the test input of the preamplifier will result in a short impulse of charge,  $Q_{\text{SW}} = C_{\text{Eq}} V_0$ , that is introduced to the charge integrator.  $C_{\text{Eq}}$  is the parallel sum of the test capacitance and any stray capacitance ( $C_{\text{Eq}} = C_{\text{Test}} + C_{\text{stray}}$ ). Fig. 4 demonstrates the pulse shapes for the square wave method when the total charge is equal to the charge created in the PD by a CsI(Tl) scintillation event ( $Q_{\text{SW}} = Q_{\text{Csl}}$ ). Since we again have an impulse of charge, this method produces results similar to the direct interaction method, and the calibration results will again depend on the choice of shaping time.

The precision to which  $C_{\text{Eq}}$  is known directly affects the precision of the calibration. For the preamplifiers used,  $C_{\text{Eq}}$  was inferred from the direct interaction method to assess the contribution of  $C_{\text{stray}}$ . The results were consistent with the nominal value of the capacitance of the test capacitor and the addition of a stray capacitance on the order of a few percent.

### 4. Shaped square wave (SSW) on $C_{\text{Test}}$

Our method to compensate for the ballistic deficit introduced by the long decay time of CsI(Tl) is to introduce a current pulse of known total charge,  $Q_{\text{SSW}}$ , with the shape of the scintillation pulse, eq. (5), to the

charge integrator. The shaped square wave (SSW) method models the scintillation pulse to satisfy this requirement. Considering the leading edge of a square wave, the pulse is split three ways, each branch passed through an integration stage (two non-inverting for the decays and one inverting for the rise), two of the branches attenuated by  $k_1$  and  $k_2$ , then all three summed before  $C_{Test}$ . This pulse will behave like

$$V_{Calib}(t) = V_0(e^{-t/\tau_{c1}} + k_1 e^{-t/\tau_{c2}} - k_2 e^{-t/\tau_{c3}}). \quad (7)$$

The current introduced to the charge integrator is

$$I(t) = C_{Eq} \frac{d}{dt} V_{Calib}(t) = C_{Eq} V_0 \left( -\frac{e^{-t/\tau_{c1}}}{\tau_{c1}} - \frac{k_1 e^{-t/\tau_{c2}}}{\tau_{c2}} + \frac{k_2 e^{-t/\tau_{c3}}}{\tau_{c3}} \right), \quad (8)$$

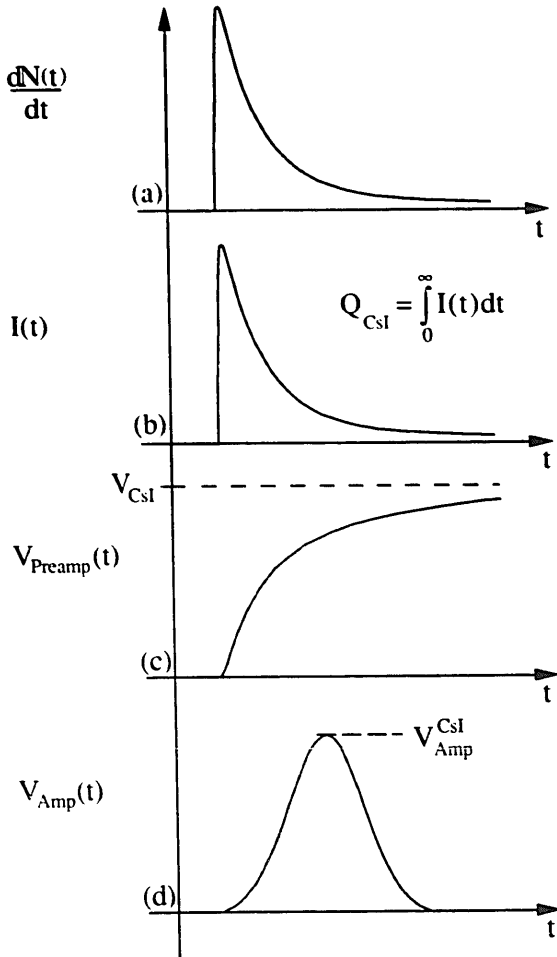


Fig. 2. CsI(Tl) pulse shapes: (a) scintillation yield, (b) preamplifier input current pulse, (c) preamplifier output voltage pulse, and (d) amplifier output voltage pulse.

while the total charge delivered to the charge integrator is

$$Q_{SSW} = \int_0^\infty I(t) dt = C_{Eq} V_0 (1 + k_1 - k_2). \quad (9)$$

The resulting preamplifier output voltage pulse will be

$$V_{Preamp}(t) = \frac{Q_{SSW}}{C_F} e^{-t/\tau_f} - \frac{C_{Eq} V_0}{C_F} e^{-t/\tau_{c1}} - \frac{C_{Eq} V_0 k_1}{C_F} e^{-t/\tau_{c2}} + \frac{C_{Eq} V_0 k_2}{C_F} e^{-t/\tau_{c3}}. \quad (10)$$

Eqs. (6) and (10) are identical when  $\tau_1 = \tau_{c1}$ ,  $\tau_2 = \tau_{c2}$ ,  $\tau_r = \tau_{c3}$ ,  $Q_{CsI} = Q_{SSW}$ ,  $Q_1 = C_{Eq} V_0$ ,  $k_1 = Q_2/Q_1$ , and  $k_2 = (Q_1/\tau_1 + Q_2/\tau_2)\tau_3/Q_1$ . Fig. 5 shows the results of the SSW method when the above conditions are satisfied. With scintillation and calibration pulses of identical shape and amplitude, the calibration is independent of shaping time because each pulse has the same ballistic deficit.

The trailing edge of the initial square wave will produce exactly the same results as the leading edge with the opposite sign. The negative pulses will pass through the amplifier, but not be recognized by the analog-to-digital converter in the multi-channel analyzer.

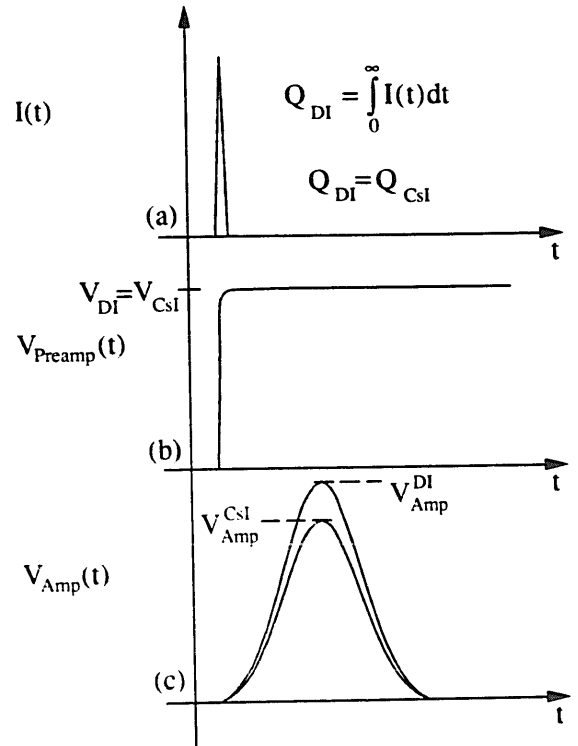


Fig. 3. Direct interaction method pulse shapes: (a) preamplifier input current pulse, (b) preamplifier output voltage pulse, and (c) amplifier current output voltage pulse.

Fig. 6 summarizes the behavior described in sections 2, 3, and 4 by showing the peak centroid for CsI(Tl) scintillation events and each of the mentioned calibration methods as a function of shaping time. As previously stated, the CsI(Tl) and SSW method yield the same results, the centroid increases with increasing shaping time, while the peak position is relatively constant for the direct interaction and square wave methods.

### 5. Shaped square wave circuit and operation

An analog circuit was designed to implement the SSW method. The circuit diagram is shown in fig. 7. A square wave with repetition period much greater than the amplifier shaping time constant is applied to the input GEN. This signal is split into three RC integration stages. The first two stages simulate the two decay time constants of CsI(Tl). Each stage consists of a

potentiometer ( $P_1, P_2$ ), a resistor ( $R_1, R_2$ ), a capacitor ( $C_1, C_2$ ), and a follower ( $A_1, A_2$ ). The time constants are  $\tau_{C_1} = (P_1 + R_1)C_1$  and  $\tau_{C_2} = (P_2 + R_2)C_2$ . The third branch, with a time constant of  $\tau_{C_3} = (R_3 \parallel R_4)C_3$ , simulates the rise time constant of CsI(Tl). The polarity of this signal is opposite of the first two branches and is achieved with an inverting amplifier,  $A_3$ . Subsequently, the signals from  $A_1, A_2$ , and  $A_3$  are introduced to an analog summer, realized by operational amplifier  $A_4$ . The signals from  $A_2$  and  $A_3$  are weighted relative to the signal from  $A_1$ . The weight of the signal from  $A_2$ , as determined by  $k_1 = Q_2/Q_1$ , is set by potentiometer  $P_3$  and the resistor  $R_7$ . Similarly,  $k_2 = (Q_1/\tau_1 + Q_2/\tau_2)\tau_3/Q_1$  is used to weight the signal from  $A_3$  and is set by  $P_4$  and  $R_8$ . The output voltage of the analog summer,  $A_4$ , represents the simulated shape of eq. (7).

The calibration signal is then applied to the input of an active divider, realized by operational amplifier  $A_5$  [4]. The divider allows the pulse amplitude,  $V_{OSC}$ , to be

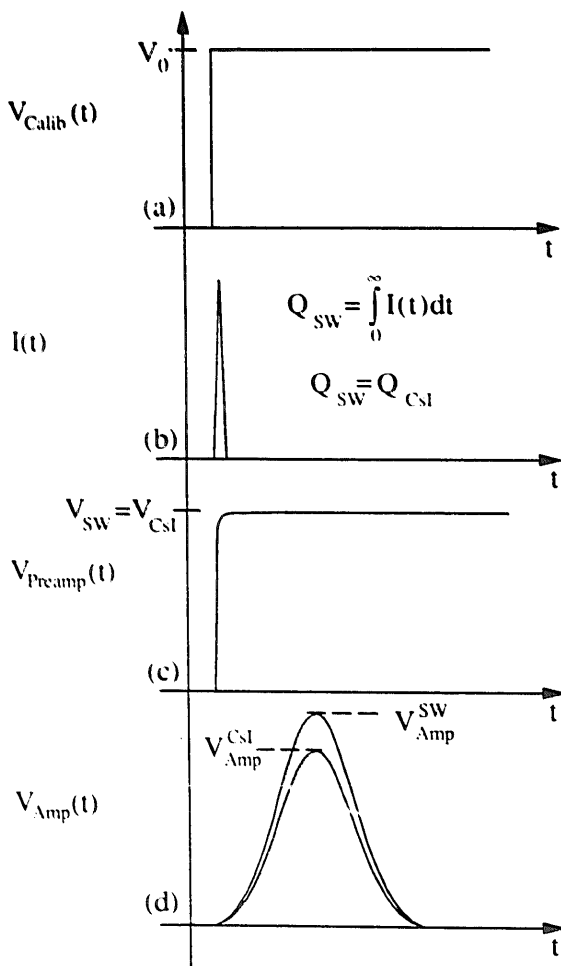


Fig. 4. Square wave method pulse shapes: (a) calibration voltage pulse, (b) preamplifier input current pulse, (c) preamplifier output voltage pulse, and (d) amplifier output voltage pulse.

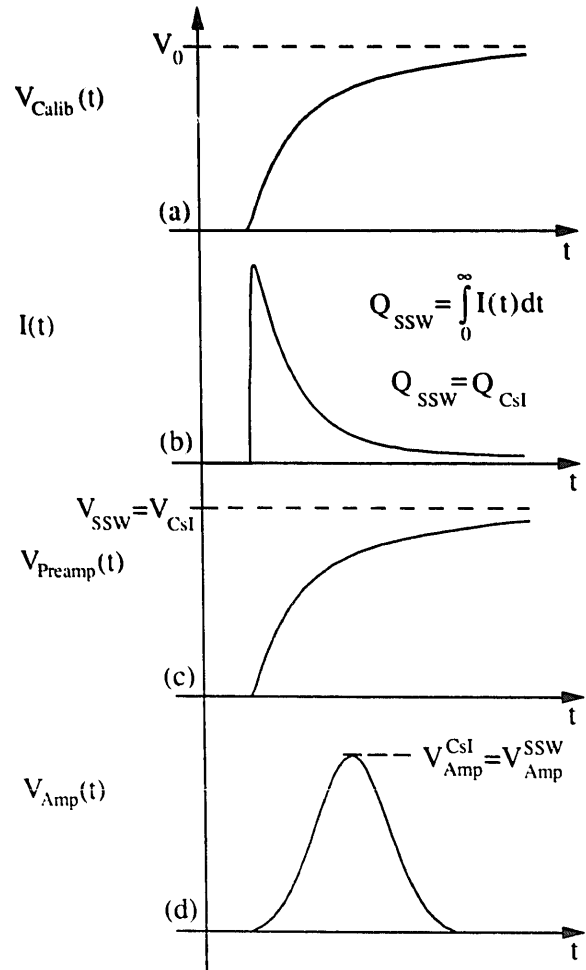


Fig. 5. SSW method pulse shapes: (a) calibration voltage pulse, (b) preamplifier input current pulse, (c) preamplifier output voltage pulse, and (d) amplifier output voltage pulse.

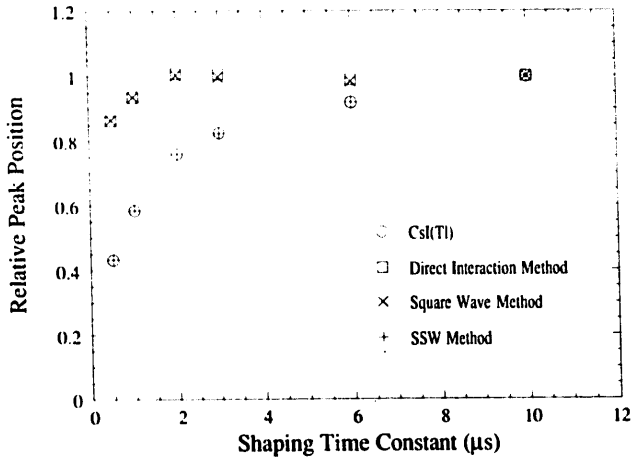


Fig. 6. Normalized CsI(Tl) photopeak and charge calibration peak centroid positions as function of shaping time.

accurately measured at the OSC output and then scaled to the desired calibration pulse amplitude,  $V_0$ , at TEST. The ratio of the divider was set to be 50:1 at the maximum value of potentiometer  $P_6$ .

To confirm the applicability of the circuit and the method, a  $1 \times 1 \text{ cm}^2$  right cylindrical CsI(Tl) crystal was mounted on a  $1 \times 1 \text{ cm}^2$  square silicon PIN PD. The results for all three calibration methods are presented in table 1. It has been estimated that the uncertainty of determining  $Q_{\text{CSl}}$  by the SSW method is 3%.

6. Discussion

Although the SSW method has been demonstrated for use with PDs only, its applicability should extend to PMTs that have a known gain. Likewise, the method could be used for calibration of any inorganic scintillator, but its use is primarily of interest when ballistic deficit makes other methods inaccurate. Scintillators

Table 1 Comparison of methods of charge calibration

Amplifier shaping time constant [μs]	Calibrated charge [e-h pairs/MeV]		
	Direct interaction method	Square wave method	Shaped square wave method
0.5	22400	22200	48000
1	27600	27700	48000
2	33400	33400	48000
3	36700	36500	48000
6	41300	41500	48000
10	44200	44600	48000

with a single decay time constant will be much easier to model with the SSW method because the use of  $k_1$  and  $k_2$  will not be necessary.

The SSW method is particularly useful when assessing light yield as a function of temperature or when the decay time constant(s) of a scintillator are unknown. In the former case, a particular method may calibrate a scintillator at room temperature, but as temperature changes so will the scintillation decay time constant(s) and the related intensity(ies). A method that does not account for these changes will not accurately determine  $Q_{\text{CSl}}$  if ballistic deficit is affecting the measurements. The SSW method provides information about the temperature dependence of the scintillation decay time constant(s), the relative intensities of the different decay modes, and the absolute intensity(ies), all because scintillation and calibration pulse ballistic deficit are equivalent.

When light collection efficiency and quantum efficiency of the system are known, the SSW method results can be used to calculate absolute scintillation yield [5].

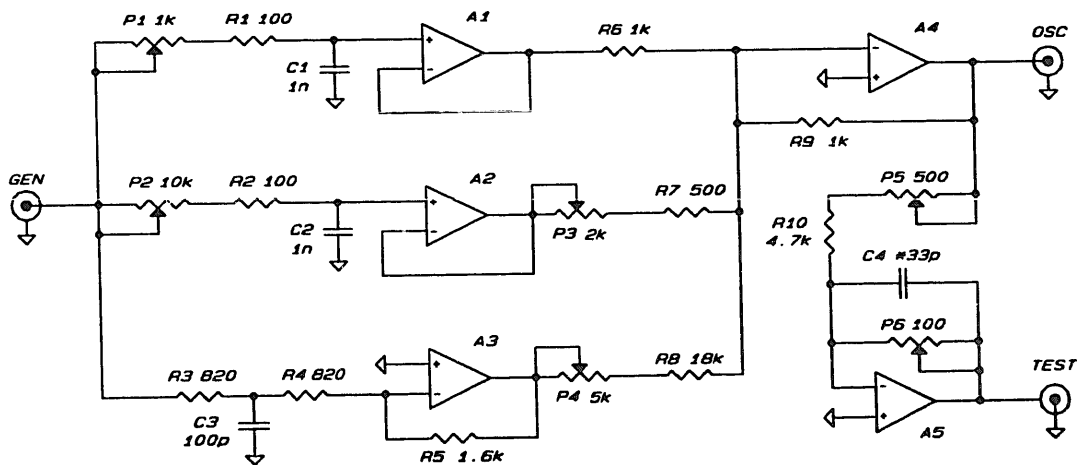


Fig. 7. SSW charge calibration circuit.

**Acknowledgements**

The authors would like to thank Tim DeVol for his invaluable discussions and insight into the scintillation spectroscopy and his measurement of the CsI(Tl) rise and decay time constants. The research was performed under appointment to the Nuclear Engineering and Health Physics Fellowship Program administered by Oak Ridge Associated Universities for the U.S. Department of Energy.

**References**

- [1] G. Knoll, *Radiation Detection and Measurement* (Wiley, 1989) pp. 278–281.
- [2] L. Bollinger and G. Thomas, *Rev. Sci. Instr.* 32 (1961) 1044.
- [3] M. Moszynski and B. Bengston, *Nucl. Instr. and Meth.* 142 (1977) 417.
- [4] Operational Amplifiers A1–A5 are HD747's.
- [5] J. Valentine, D. Wehe, G. Knoll and C. Moss, Temperature Dependence of Absolute CsI(Tl) Scintillation Yield, to be presented at the 1991 IEEE Nuclear Science Symposium.