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Abstract-- A variation of the basic Cockroft-Walton (C-W) Voltage Multiplier circuit design may be used to generate multiple voltages at sufficient currents to drive the dynodes of a photomultiplier tube. In a battery-operated handheld device, the current draw on the batteries must be kept to a minimum. Several other parameters must be considered carefully during the design as well. Components must be chosen based on size restrictions, expected load current, expected output voltage range, and the maximum allowable ripple in the output voltage. A prototype surface mount C-W board was designed and tested to power two photomultipliers. The whole system, including the detectors, draws less than 15mA of supply current with the outputs at 1000VDC.

I. INTRODUCTION

Photomultiplier tubes (PMTs) are used extensively in the nuclear industry as a method of radiation detection. One of the problems associated with the use of PMTs is the need to use a high voltage power supply. The power supply usually does not need to provide a large amount of current, but it does need to produce the multiple output voltages needed to drive the dynodes of the PMTs. Other important considerations for use with a handheld, battery-operated device include maximizing the lifetime of the battery by minimizing current draw and making the power supply as small as possible. Because of the existence of high voltages (usually on the order of 1KV) during operation, a method of ensuring operator safety from a potential shock hazard must be incorporated. Additionally, there should be a mechanism to allow a quick discharge of high voltage when the power is turned off. Several vendors provide small, encapsulated power supplies that meet the high voltage requirement, but they have several limitations, which make them unsuitable to be used in a battery-operated device. One such vendor is Emco High Voltage Corporation [1]. Emco produces a small (~ ½" x ½" x ½"), modular power supply (Q10-5) with an input voltage variation of 0 to 5VDC, which produces the output voltage variation from 0 to 1000VDC. Unfortunately, the source current required to drive this power supply is substantial (about 150mA with the output voltage adjusted to 1000VDC). An additional drawback of using PMT devices is the derivation of individual dynode voltages for the PMT. Since only the highest voltage is provided from the power supply, all dynode voltages must be produced by way of a voltage divider. This voltage divider uses additional battery current.

Voltage Multipliers, Inc. (VMI) [2] has several web pages showing how to calculate the theoretical values of ripple voltage, regulation, and stray capacitance for a specific design of the Cockroft-Walton voltage multiplier. In practice, the actual circuit components selected and the board layout will determine the specifics of characteristic data. Many of the formulas on these pages serve as a good starting point in any design.

In this work, a small high-voltage surface mount board was designed and developed that takes advantage of the benefits of the Cockroft-Walton design while considerably minimizing the board size. The design includes access to the individual dynode voltages of the multiplier circuit, which precludes the necessity of a voltage divider circuit. The resulting design requires a small current to drive multiple PMTs using a compact printed circuit board and can be totally self-enclosed to minimize the risk of an operator shock hazard.

II. BOARD DESIGN AND TESTS

The current application that this board is designed for requires the use of two PMTs. To drive the dynodes of the PMT devices, a total of 9 stages of voltage multiplication were needed (plus the ground reference), with a multiplication of the input peak-to-peak voltage between all stages except the last. The last stage is one half the input peak-to-peak voltage from the previous stage for the PMT devices employed (Hamamatsu R7400P [3]).

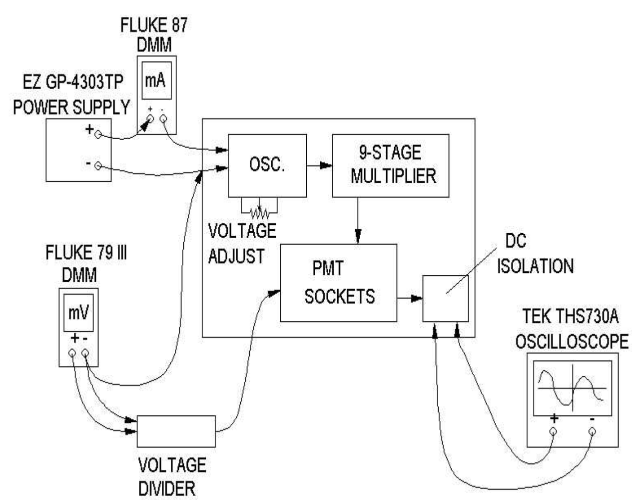

Fig. 1. Block Diagram of Test Setup.

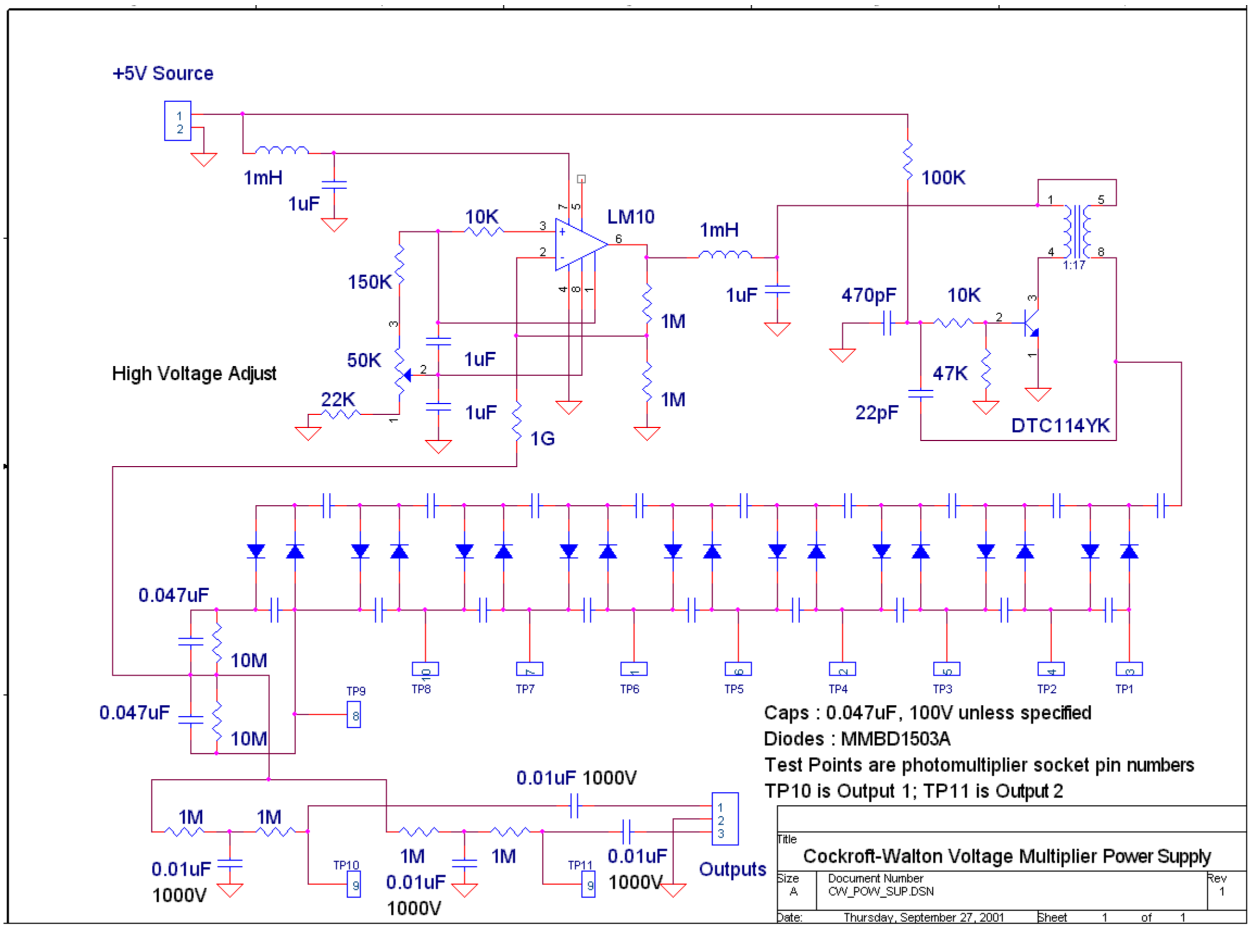

Fig. 2. Schematic Diagram of the Test Setup.

A voltage divider (using high ohmic value resistors) was used between the 8th and 9th stages to derive the anode voltage. Another alternative to consider is to use one half the required dynode voltage per stage, and use every other stage of voltage to drive the dynodes. While this approach would draw less current (no voltage divider needed), it requires the use of additional stages (17 stages as opposed to 9 stages), and therefore more parts. Moreover, a set of filter capacitors would be required between every other stage to drive the dynodes. This approach was abandoned because it would have increased the size as well as the cost of the board.

The two main components shown in the block diagram (Figure 1) are the oscillator and the voltage multiplier. The oscillator section takes a DC input voltage (~5VDC to 6VDC) and converts it to an AC sine-wave output. The peak-to-peak (p-p) output voltage from the oscillator section is a function of the turns ratio of the oscillator transformer and a level adjustment to the op-amp of the oscillator. The characteristic frequency of oscillation is primarily due to the inductances of the transformer windings and the capacitance of the feedback capacitor. With the values selected (see Figure 2.), the maximum AC sine-wave output amplitude was about 120VAC, p-p. The frequency of oscillation was about 780KHz. The output of the oscillator section is passed as the input to the voltage multiplier section. The multiplier section is composed of nine stages.

The operation of the multiplier is to effectively multiply the peak-to-peak AC input voltage by the number of stages and convert each output to a DC voltage. For instance, with the oscillator output voltage set to 100VAC, p-p, the voltage at the 1st stage of multiplication is 1 X 100VAC, p-p, or 100VDC. The voltage at the 9th stage of multiplication is 9 X 100VAC, p-p, or 900VDC. In practice, however, these theoretical values were somewhat reduced due to losses in the diodes, stray capacitances and leakage currents of the diodes, component tolerances of the diodes and capacitors, etc. The regulation, or the deviation from the ideal output voltage due to current load, is proportional to the cube of the number of stages in the multiplier [2]. The actual DC voltages obtained also decreased due to the output current loading. Between the 8th and 9th stages is a voltage divider that provides the one-half stage voltage for the anodes of the PMTs. The values for the resistors used in this voltage divider are chosen to be high enough to minimize the effects of the current load introduced by the divider. In the actual prototyped circuit, we used 10Mohm resistors because of availability.

The total input current measurement was taken at the power supply input to the oscillator circuit. The primary contributions to the total source current are from the oscillator and the load current in the voltage divider.

Current losses in the multiplier capacitors are directly proportional to the frequency of operation of the oscillator [2].

The outputs of the voltage multiplier were applied to a pair of sockets into which the Hamamatsu R7400P PMTs were inserted. The outputs from the PMT devices were AC coupled to isolate the high DC voltage potential for further processing by downstream electronics. The voltage rating on these AC coupling capacitors had to be high enough to handle the expected anode voltage on the PMT devices. The vendor selected for these capacitors (Cal-Chip [4]) provides high-voltage components with a small footprint. During development, it was noted that monitoring the stage voltages with a standard digital multimeter (DMM) substantially loaded the reading due to the input impedance of the DMM itself. This effect was much more noticeable on the upper stages. Therefore, a voltage divider composed of a 1Gohm 2% resistor in series with a 10Kohm 1% resistor was used. The voltage across the 10Kohm resistor was a factor of 1/100,001 of the actual voltage being monitored. For instance, a reading of 9.5mV on the DMM corresponded to an actual voltage reading of 950VDC. An external precision power supply was used to calibrate the voltage divider. We used 1Gohm resistors from Ohmcraft [5] for the surface mount board.

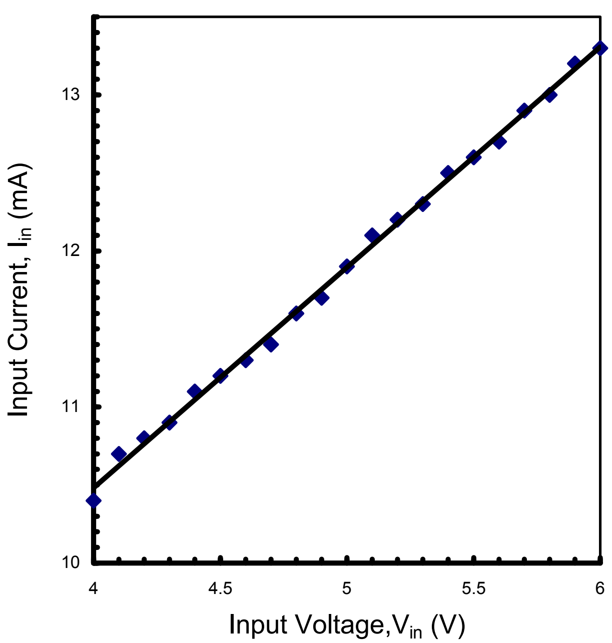

Fig. 3. Input Current vs Input Voltage.

The primary selection criteria for commercially available transformers were size and turns ratio. The turns ratio had to be substantially high to provide the high secondary voltage needed (about 100VAC, p-p). Sprague-Goodman [6] supplied a standard component with a usable turns ratio (1:17) that had a small size (~ ¼" x ¼" x 1/8"). The small footprint of the transformer fit well into the prototyped circuit design.

Upon examination of the signals coming from the high-voltage coupling capacitors, it was noted that a large component of oscillator frequency noise remained. A large portion of this noise was being electromagnetically coupled due to the open-frame design of the Sprague-Goodman transformer and the high frequency of operation of the oscillator. It was necessary to minimize the amount of output ripple voltage. Output ripple voltage is directly proportional to the square of the number of stages and inversely proportional to the frequency and size of the capacitors used in each multiplier stage [2]. The actual selected value for the capacitors was found by making the value as high as possible for the expected working voltage while still maintaining as small a circuit footprint as possible. Much of the noise in the output was found to be common mode (the noise appeared on the ground line as well as the signal lines).

Figure 3 shows the circuit board input current measurement as a function of the input voltage. Input voltage was varied from 4.0VDC to 6.0VDC to approximate the variations that might be expected during the usable lifetime of a set of four AA batteries. The solid line is the least square fit to the data, which shows the linear relationship between input voltage and input current.

One item of concern in implementing a portable, battery-operated, high-voltage circuit is the risk of shock to a user and to anyone having to perform routine maintenance on the circuit. The incorporation of a 1Gohm, surface mounted resistor connecting the high-voltage line to ground provided the path to bleed off the high-voltage to a ground potential while presenting a minimum impact to total current draw.

A preliminary surface mount board design, which includes the sockets for two PMTs, is shown in Figure 4. This board size is about 1" x 3 ½" and can be further reduced if only one PMT is needed. A potting compound could be applied over the whole board, except for the input terminals, output terminals, and PMT sockets, to reduce the exposure to the high voltages. The utilization of surface mounted components reduces the total circuit board size. The majority of the connection traces are on the component side of the board. A few connection traces between the PMT sockets are incorporated on the opposite side of the board so care must be given to exposed shock hazards on both sides of the board. The majority of the opposite side of the board is ground plane to help in reducing the noise level. For a design utilizing only one PMT device, all high voltage lines could easily be laid out on one side of the board.

One of the applications that this C-W board will be used is in a small device to simultaneously detect neutrons and gamma rays [7]. This will be accomplished by using two ^{6}Li and ^{7}Li glass scintillators (8mm in diameter and 2mm thick). These detectors are mounted on two Hamamatsu photomultipliers labeled "6" and "7" as shown in Figure 4.

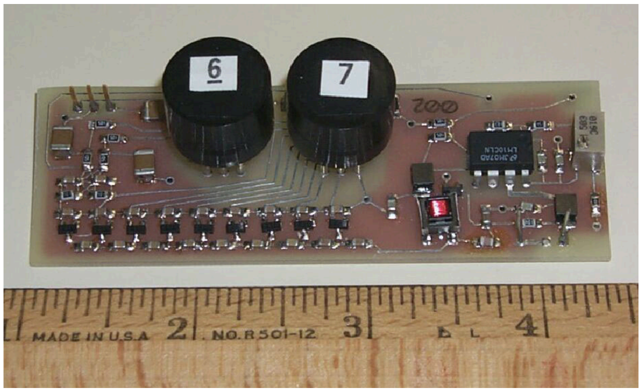

Fig. 4. C-W Board and Mounted ^{6}Li / ^{7}Li Detectors.

Figure 5 shows the spectra taken with a ^{252}Cf source. Both ^{6}Li and ^{7}Li spectra are overlapping in the low-energy region indicating that they are equally sensitive to gamma rays. By subtracting the ^{7}Li spectrum (gamma) from the ^{6}Li spectrum (neutron + gamma) we can obtain the pure ^{6}Li spectrum (neutron).

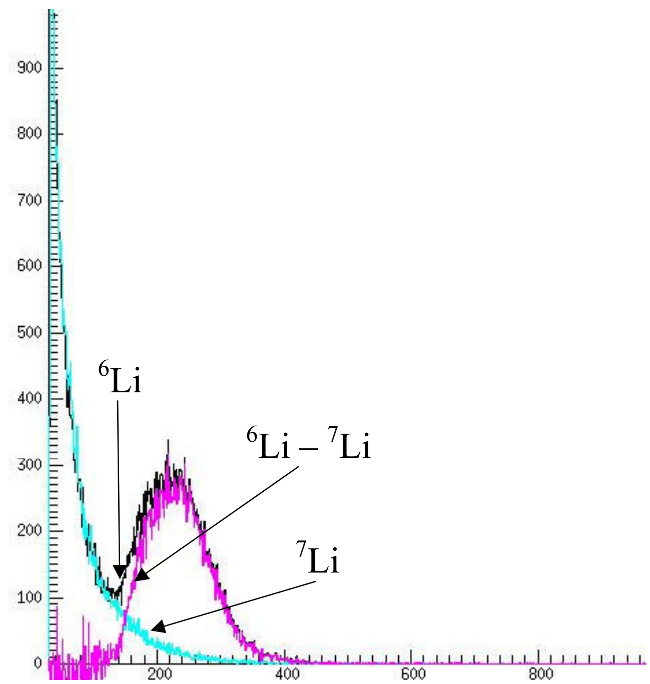

Fig. 5. ^{6}Li, ^{7}Li, and (^{6}Li – ^{7}Li) Spectra.

III. CONCLUSIONS

A small Cockroft-Walton surface mount was designed and tested for use in a battery-operated and palm-sized radiation detection device. In addition to circuit components, this board contains sockets to drive two Hamamatsu R7400P PMTs. This is to minimize the exposed area of high voltage and therefore to reduce any possible shock hazard. The whole system, when attached to a pair of detectors, draws very little current (< 15mA). The size of the complete high voltage printed circuit board is very small, including the oscillator and PMT sockets, measuring about 1” x 3 ½”. If the total output ripple voltage and noise is a concern, a filter may be applied to the output signal and ground lines to substantially reduce the noise amplitude.

IV. ACKNOWLEDGEMENT

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V. REFERENCES

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