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The Cockcroft-Walton Photomultiplier Tube Base And The Ethernet High Voltage Controller*

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Abstract

A new development on the Cockcroft-Walton photomultiplier tube base and the Ethernet high voltage controller is described. This high performance system is characterized by its low heat dissipation, low noise, total elimination of high voltage cables, and the capability of remote operation on the Ethernet network. It is particularly suitable for applications in large scale collider experiments.

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1 Introduction

The calorimeter of the electron-proton collider experiment. ZEUS. at DESY in Hamburg. Germany. is made of depleted uranium and plastic scintillator plates. It uses over ten thousand photomultiplier tubes. There are three major concerns about its high voltage system. They are: 1) the safety problem. 2) the heat dissipation. and 3) the cabling and control. Since depleted uranium is used in the calorimeter, safety has become one of the most important issues. One possible scenario is that the high voltage cables might get inadvertently crushed and the subsequent sparking could lead to a fire hazard. Therefore, it is most desirable not to have over 10^4 high voltage cables running through the calorimeter. In addition to the safety problem, the holes they occupy will reduce the acceptance of the detector. If conventional tube bases (made of resistors and capacitors, and sometimes a few Zener diodes are added) are used, each base can generate 1~2 watts of heat. The cooling requirement can only add more difficulties to an already over cramped space. To stabilize the gains under high counting rate conditions, normally the last few dynodes have to be stiffened by connecting them to external low voltage power supplies. This requires additional cabling. It is obvious that a new approach has to be sought to meet these requirements, which led to the development to be described in this paper.

2 The Cockcroft-Walton Photomultiplier Tube Base

A satisfactory solution, developed at Virginia Tech, is to build a small *Cockcroft-Walton accelerator*[1] for each photomultiplier tube[2]. A ~60 kHz oscillator is powered by a 24 volts d.c. power supply. The pulses are then stepped up to ~100 volts by a ferrite transformer. This radio-frequency power is used to drive a *Cockcroft-Walton accelerator*, consisting of a chain of rectifiers and capacitors, to produce the desired high voltage. The high voltage is monitored through a 70 MΩ potentiometer, which gives a reduction factor of 1000:1. This feedback signal is also used to regulate the high voltage by modulating the amplitude of the oscillator. Since the high voltage chain consists of only capacitors and diodes, naturally there is very little energy loss. The main source of heat generation is from the hysteresis loss of the ferrite transformer and the feedback circuit. The gain stability of the photomultiplier tube. under high counting rate conditions, can be easily maintained by using larger capacitors at the last few dynodes. In addition, the energies stored on these capacitors are replenished at the frequency of the oscillator.

[1] J.D. Cockcroft and E.T.S. Walton, Proc. Roy. Soc. (London) **A137**, 229(1932).

[2] B. Lu, L.W. Mo and T.A. Nunamaker, "The Cockcroft-Walton Photomultiplier Tube Base and Test Results," ZEUS-Note 88-036 and AMZEUS-56, 1988, unpublished.

The schematic diagram of the Cockcroft-Walton photomultiplier tube base is shown in Fig. 1. The whole assembly is housed in a small cylindrical container, 2.4″ in length and 1.5″ in diameter.

3 The Performance

The obvious difficulties we have to address for such a new type of tube base are:

- **Noise:** The output circuit could pick up a great deal of noise from the oscillation of ~100 volts in amplitude and ~10^5 Hz in frequency.
- **Linearity Range:** The voltage division is quantized by the *Cockcroft-Walton accelerator* chain and they cannot be easily changed to arbitrary values. However, the small diameter photomultiplier tubes we are using prefer to have uneven voltage distributions on the dynodes in order to achieve the highest gain and the maximum dynamic range of linearity.
- **Construction:** The ideal construction of the Cockcroft-Walton tube base is to build as many stages as possible (e.g. several times the number of stages of the photo-tube), which will definitely offer the flexibility for fine-tuning the high voltage distributions on the dynodes. As a consequence, the dynamic range can be increased. However, this is not practical. By connecting more capacitors in series, the effective capacitance and the stored energy will both become smaller which can degrade the performance. Space, noise pickup, and cost will all impose severe limitations to defeat the effort.

In the following sections, we will describe how we dealt with these problems.

3.1 The Noise

Noises of the base were reduced to a satisfactorily low level by proper grounding and shielding. Pickups from the oscillator were compensated to an almost null level at the output circuit by a feedback network which reversed the phase of a small synchronous signal tapped at the ferrite transformer. Fig. 2 shows a spectrum measured at 1,300 volts with a charge injector. In order to examine the detailed structure of the noise, the signal from a photomultiplier tube base was amplified first by a factor of ~25; then it was mixed with the output of a charge injector and fed into a 12-bit ADC (analogue-to-digital converter). Typically, the σ value of the distribution was measured to be ~1.4 channel, where the calibration constant was 1.3×10^{-14} Coulombs per channel. The noise of the amplifier was measured by turning off the high voltage, and found to be $\sigma \simeq 0.89$ channel. After subtraction by quadrature, the noise of the Cockcroft-Walton tube base at 1.300 volts was found to be $\sigma \simeq 1.4 \times 10^{-14}$ Coulombs, which is approximately the same as that of a conventional resistive tube base.

3.2 The Linearity Range

It was known that if the high voltages were distributed evenly on the dynodes of a small size and high gain photo-tube (such as the XP2011 and XP1911 made by Philips, and R580 made by Hamamatsu), the output pulse shape would become wider when operated at higher gains because of the space charge effect. This effect can be reduced by using uneven voltage distributions at the last few dynodes. Also, the first dynode has a large effect on the tube gain because of its focussing action. Therefore, its voltage has to be optimized. These studies were carried out with resistive bases because their configurations can be changed easily, which is not the case for the Cockcroft-Walton bases. The exercise was to find a configuration for the Cockcroft-Walton base which could best approximate the optimum solution. Before we go on to discuss the results, the testing procedure will be introduced first in order to better clarify a few important points.

3.3 Testing Procedure

The quantum efficiency of a photomultiplier tube depends strongly on the wavelength of the light incident upon the photo-cathode. The best way to measure the linearity of the system is to use a *calibrated* blue LED (light emitting diode), and measure the output signal of the base as a function of the number of incident photons with the high voltage fixed. Unfortunately, the high intensity blue LED's for wavelength in the range of 400~500 nm are not available. The only way to reach high gains with a weak blue LED is to apply higher voltages on the photomultiplier tube, since the gain of a photomultiplier tube is proportional to $(V/V_0)^n$, where $n \simeq 7$.

At lower voltages, such as the operating point of ~1,300 volts, the photomultiplier tube can be driven to saturation with a red LED ($\lambda \geq 660$ nm) which gives a far more intense light output than the blue LED's. In order to interpret the test results without ambiguities, we decided to simplify the method of measurement by looking only at the pulse shape from the base on a digital storage oscilloscope. An almost *matching pair* of red LED's was operated under identical conditions. They could be fired individually or simultaneously by discharging separate capacitors (charged to the same voltage) through gated transistor switches. The individual output pulse produced by triggering a single LED, as well as that by triggering two LED's simultaneously under identical settings, were recorded by a digital storage oscilloscope. The test setup is shown schematically in Fig. 3. By comparing these pulses, one can quickly decide whether the tube is saturated or not. The full width at half-maximum of the output pulse generated by the red LED was ~25 nsec.

After solutions were found by the aforementioned method, the linearity was checked again with a blue LED of wavelength ~490 nm. The setup is shown schematically in Fig. 4. The light beam was split by a mirror. One beam illuminated the photo-tube cathode, the other went into a photo-diode detector. The output of the photo-diode was used to stabilize the pulse generator which fired the blue LED. This arrangement provided an excellent calibrated light source (±1%), at the expenses of low light intensity and long pulse width (≤300 nsec).

3.4 Test Results

After a number of configurations of voltage distributions were tried, the following facts were observed:

- The first dynode should have two units of voltage to provide better focussing, where one unit is the voltage of a single stage of the Cockcroft-Walton accelerator.
- For the photomultiplier tube, R580 made by Hamamatsu, a fairly good solution was found by distributing high voltages from anode to the first dynode according to the ratio $3:2:2:2:1:\cdots:1:2$; and for the tube XP1911 made by Philips, $3:2:2:2:1:\cdots:1:2:1:2$.
- The anode stage definitely needs more voltage to reduce the space charge effect. The manufacturers recommended otherwise. We found that the tube-dependence of the linearity range would become more serious if such recommendations were followed.
- Once the approximate distribution of voltage is selected, the linearity range does not depend critically upon the fine tuning.
- Linearity range of the Cockcroft-Walton base is identical to that of the ***high current*** resistive base if their voltage distributions are approximately the same.
- When the counting rate is high, the gain of the Cockcroft-Walton base is stable as indicated by tests with a strong radioactive ^{90}Sr source.
- The power consumption of a Cockcroft-Walton base is ~0.12 watts. It should be compared to that of a resistive base, 1~2 watts depending upon the counting rate requirement.

The linearity measurement for R580, using two red LED's, is shown in Fig. 5; and that of utilizing a calibrated blue LED is shown in Fig. 6. It should be noted that the linearity range provided by the particular configuration of voltage distribution we chose for the tube, R580, is ~160 ma at 1,300 volts, instead of 200 ma as that claimed by the manufacturer. For the 19 mm diameter tube, XP1911 made by Philips, the linearity range was found to be ~100 ma at 1,700 volts while the manufacturer recommended 80 ma at that voltage. This dynamic range should be adequate because it produces a peak voltage of 8 volts in a 50 Ω load impedance, while most ADC's can accept only a peak voltage of 2 volts.

4 The High Voltage Controller

In order to quickly put the Cockcroft-Walton bases into service for testing the BCAL (barrel calorimeter) modules, Virginia Tech has built the high voltage controllers in stages. Controllers based on CAMAC data bus were first built. Then a compact and brand new VME controller was brought up into operation with RS232 communication channel. The final product is to replace the RS232 communication channel with the Ethernet, running with TCP/IP protocols.

4.1 The CAMAC High Voltage Controller

Each CAMAC high voltage controller module can set, measure and regulate the high voltages of 32 Cockcroft-Walton bases individually. All low voltage d.c. powers (24 volts for the oscillator and ±6 volts for controls) are also derived from the CAMAC module. This system was used initially in the cosmic ray test at the Argonne National Laboratory, and in the beam test at Fermilab, of the BCAL modules.

4.2 The Ethernet High Voltage Controller

The final high voltage controller for BCAL is a brand new system. There are 32 controller stations, one for each BCAL module, installed on top of the middle section of the outer supporting plates. The controller station is fairly compact in size. The outer dimension of its housing measures 6.75″ × 6.26″ × 8.90″. A photograph is shown in Fig. 7.

Each controller station contains one computer card and six analogue cards. Thirty-two Cockcroft-Walton bases can be plugged into one analogue card. Therefore, each station can handle 192 bases even though only 162 bases are used on each BCAL module.

The high voltage controller station is shown schematically in Fig. 8. The computer board contains one microprocessor (68HC11, made by Motorola), one Ethernet controller (DP8390, made by National Semiconductor), memory, and application programs stored in an EPROM. This arrangement frees the users from the tedium of writing interface softwares. It is essentially an industrial standard "turn key" system as far as users are concerned. The database for high voltage settings is downloaded from the data acquisition computer, via Ethernet, to the local memory. The microprocessor will then execute the commands to set, regulate and measure the high voltages on each photo-tube base. The photo-tube bases are plugged into the analogue cards, which provide the +24 volts power to the bases. On each analogue card, there is one 12-bit ADC and one 12-bit DAC (digital-to-analogue converter). Through a multiplexor, the ADC measures the high voltages on the photomultiplier tubes; and the DAC changes their high voltage settings.

It should be noted that the use of Ethernet greatly simplified our cable connections for the high voltage controllers. All 32 controller stations are daisy-chained to one single 50Ω, thin Ethernet, coaxial cable. This system offers an interesting feature: it can be operated remotely via the network.

On the computer card there is also a RS232 communication channel. It was installed there for initial testing before the Ethernet channel became fully functional.

4.3 The Software

The standard TCP/IP protocols are used in the Ethernet communication channel on the computer card. Only the "tftp" (*trivial file transfer protocol*) is implemented in the software because the transactions involve only the transferring of very simple tables for high voltage settings. On the command level, the following program fragment is sufficient for each controller station:

```
tftp internet-address     !call the high voltage controller station.
put table                 !download the table for high voltage settings.
(get table)               !(use this statement to read high voltages.)
quit                      !finish and exit.
```

The table for high voltage settings is an ordinary text file, which contains the serial number of the photomultiplier tube bases and their high voltage settings. This database can be prepared either by using a text editor, or automatically by requiring that the signals produced by the radiation from depleted uranium have to appear at specified ADC channels. The variants of this basic program fragment can be easily made to turn the high voltages on and off, or to change the high voltage of a single channel. In order to insure the security of system operation, a 32-bit code word is inserted at the beginning of each table of high voltage settings. The program will first check this code word for every "tftp" transaction. A discrepancy will result in an immediate abortion of the transaction to insure the integrity of the high voltage system.

The high voltage on the photomultiplier tube is kept constant mainly by the analogue feedback loop. Additional stabilization action can be introduced by the data acquisition computer. For example, if the read-back high voltage differed from the desired high voltage by an amount larger than a preset tolerance, the data acquisition computer can download a new value, calculated according to a predefined algorithm, to the high voltage controller to make the necessary corrections. The long term stability of the whole system is exhibited by Fig. 9. In a period of ~800 hours, the high voltage of a typical photomultiplier base was stable to a variance value of $\sigma \simeq 0.3$ volts; and the signals from the depleted uranium were stable to approximately $\pm 1\%$, where the statistics were from the counting rates only. These results were obtained without the explicit intervention of the data acquisition computer as aforementioned.

5 Summary

For the barrel calorimeter of the ZEUS experiment at DESY, Virginia Tech built over 5,200 Cockcroft-Walton bases and high voltage controllers. Typically, their performance can be summarized as the following: the high voltage can be stabilized to ~0.3 volts; the heat dissipation, ~0.12 watts; and for the noise, $\sigma \simeq 1.4 \times 10^{-14}$ Coulombs, which is about 1% of the energy deposition in the calorimeter by a minimum ionizing particle. The Ethernet high voltage controllers simplify the interface effort and offer the mode of remote operation. Most important above all, the acceptance of the detector is maximized because of the elimination of the huge quantity of cables. Also, the system is more economic for a large detector. It should find applications in large detectors at the SSC (*Superconducting Super Collider*).

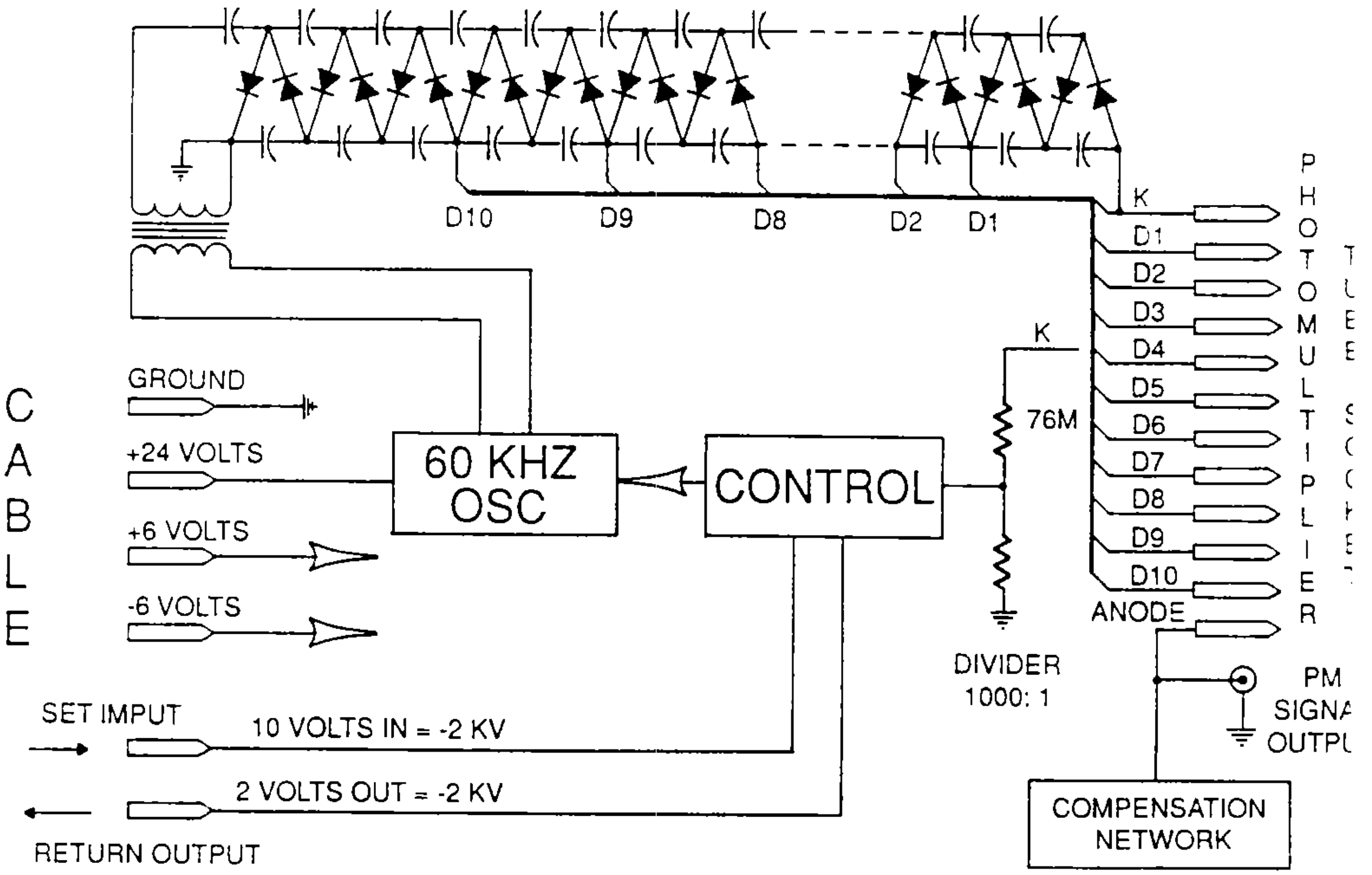


Figure 1: Schematic diagram of the *Cockcroft-Walton accelerator* type photomultiplier tube base.

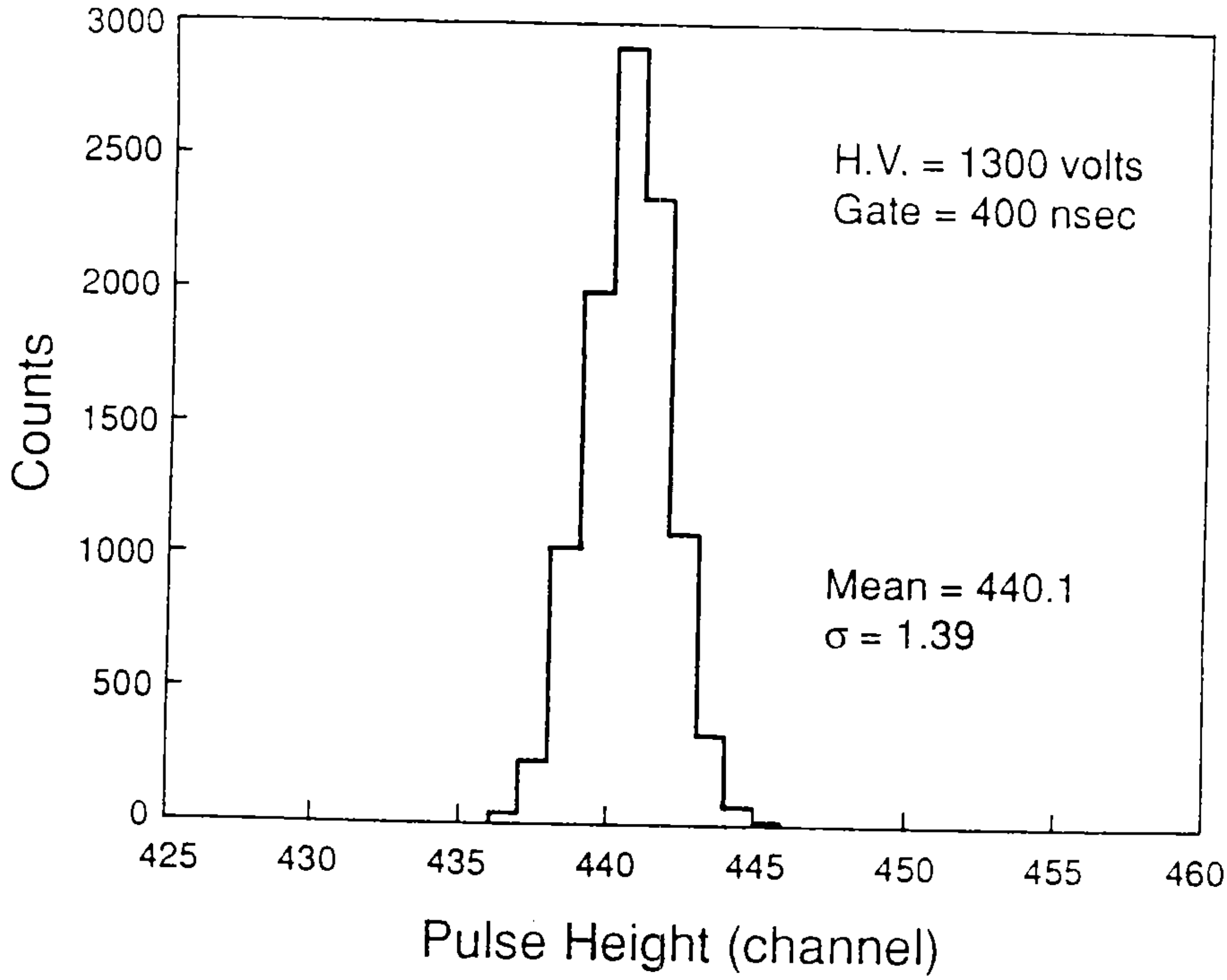


Figure 2: Noise spectrum of the Cockcroft-Walton photomultiplier tube base. It was measured with a charge injector and an amplifier of gain 25. The high voltage was set at 1.300 volts for a Hamamatsu R580 photo-tube.

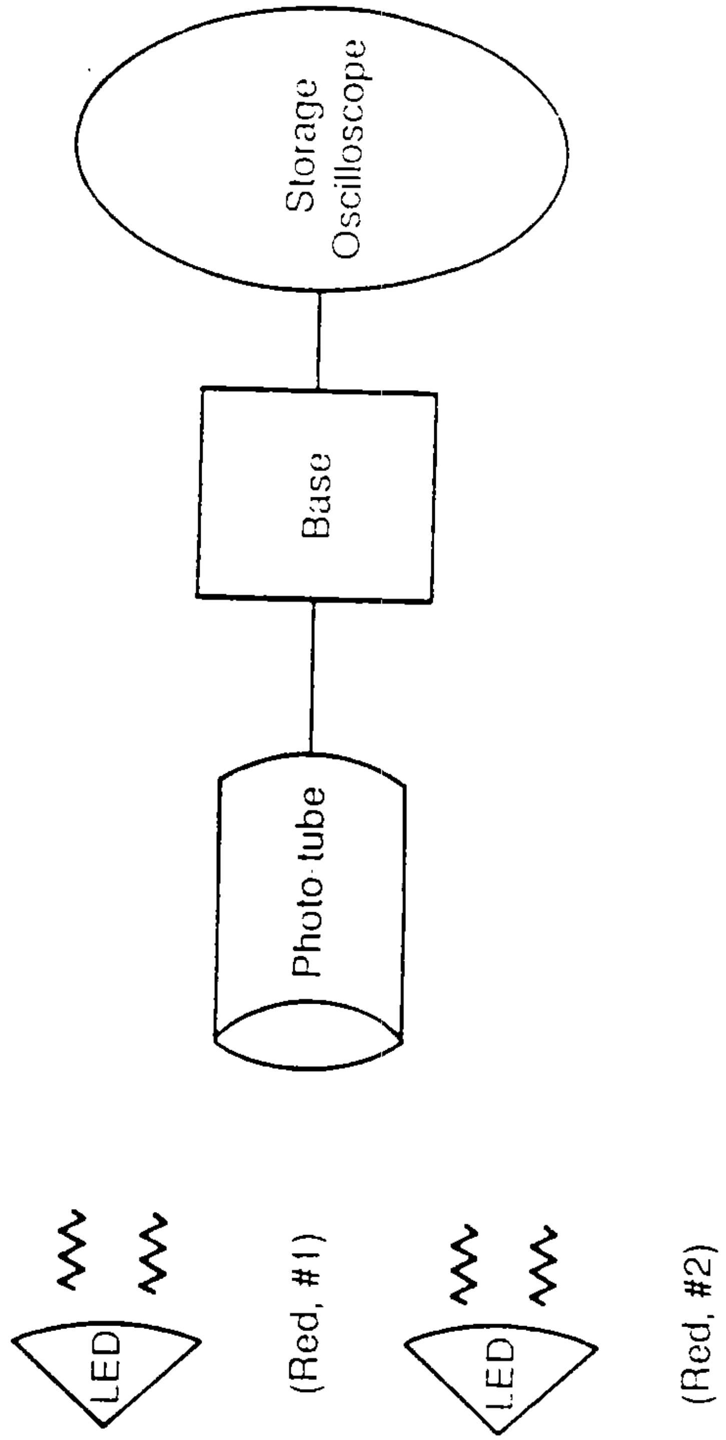


Figure 3: Schematic diagram of the setup for testing linearity ranges of photomultiplier tubes with two red LED's.

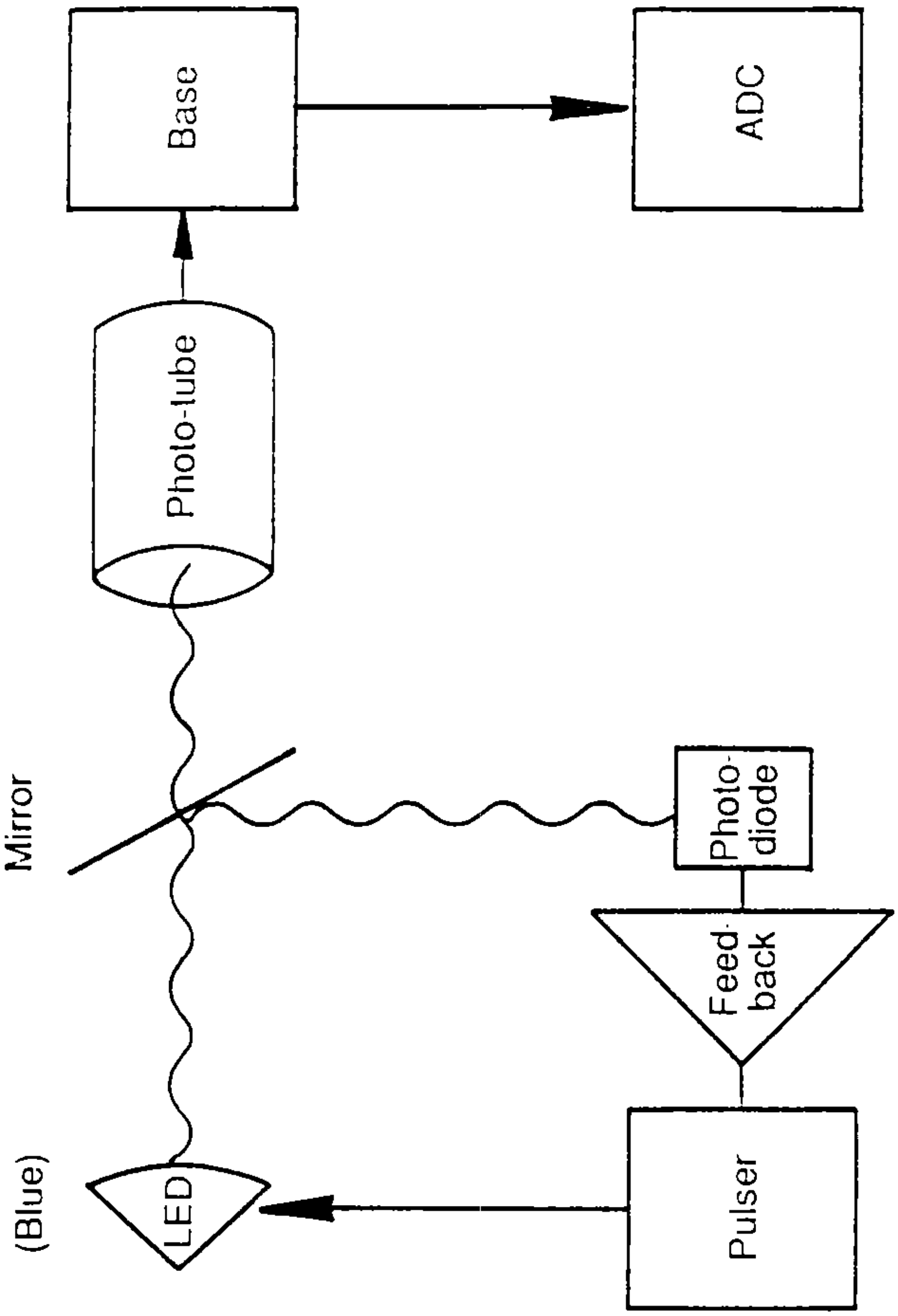


Figure 4: Schematic diagram of the setup for testing linearity ranges of photomultiplier tubes with a calibrated blue LED.

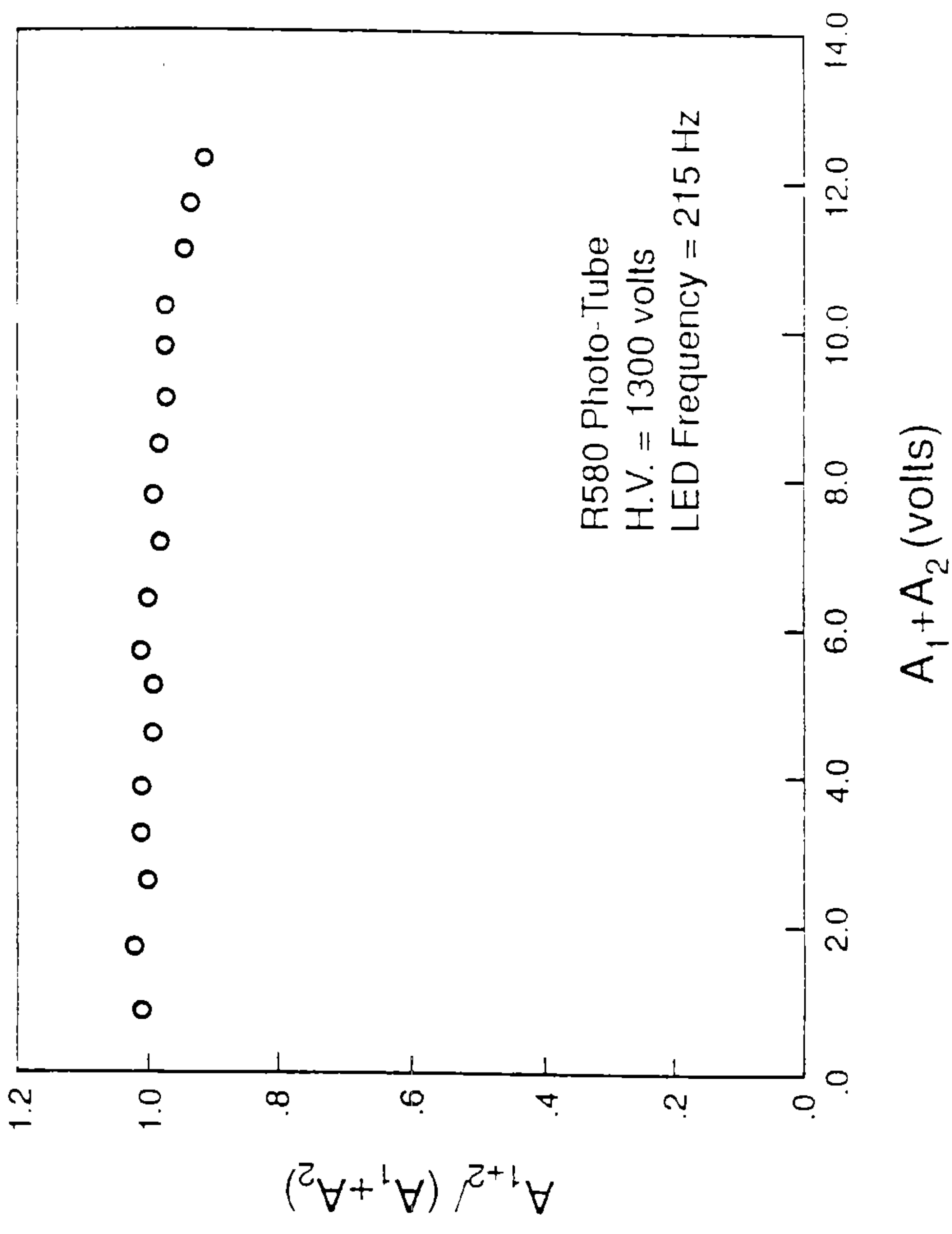


Figure 5: Linearity of the Cockcroft-Walton base for a R580 photo-tube measured with two red LED's: where A_1 and A_2 represent the peak voltage when each LED was fired individually, and A_{1+2}, the amplitude when both LED's were fired simultaneously.

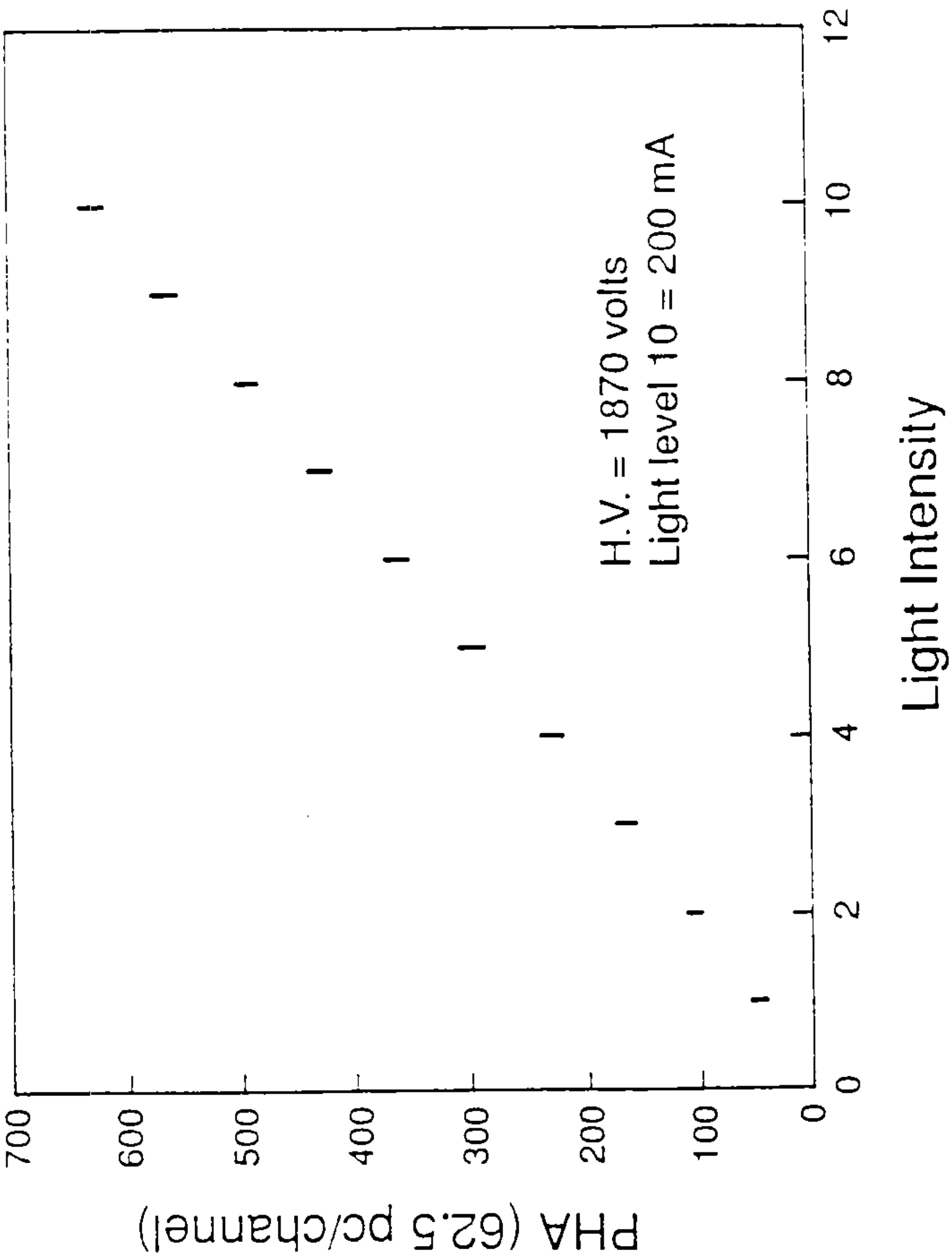


Figure 6: Gain of the Cockcroft-Walton base with a R580 photo-tube vs the incident light intensity from a calibrated blue LED.

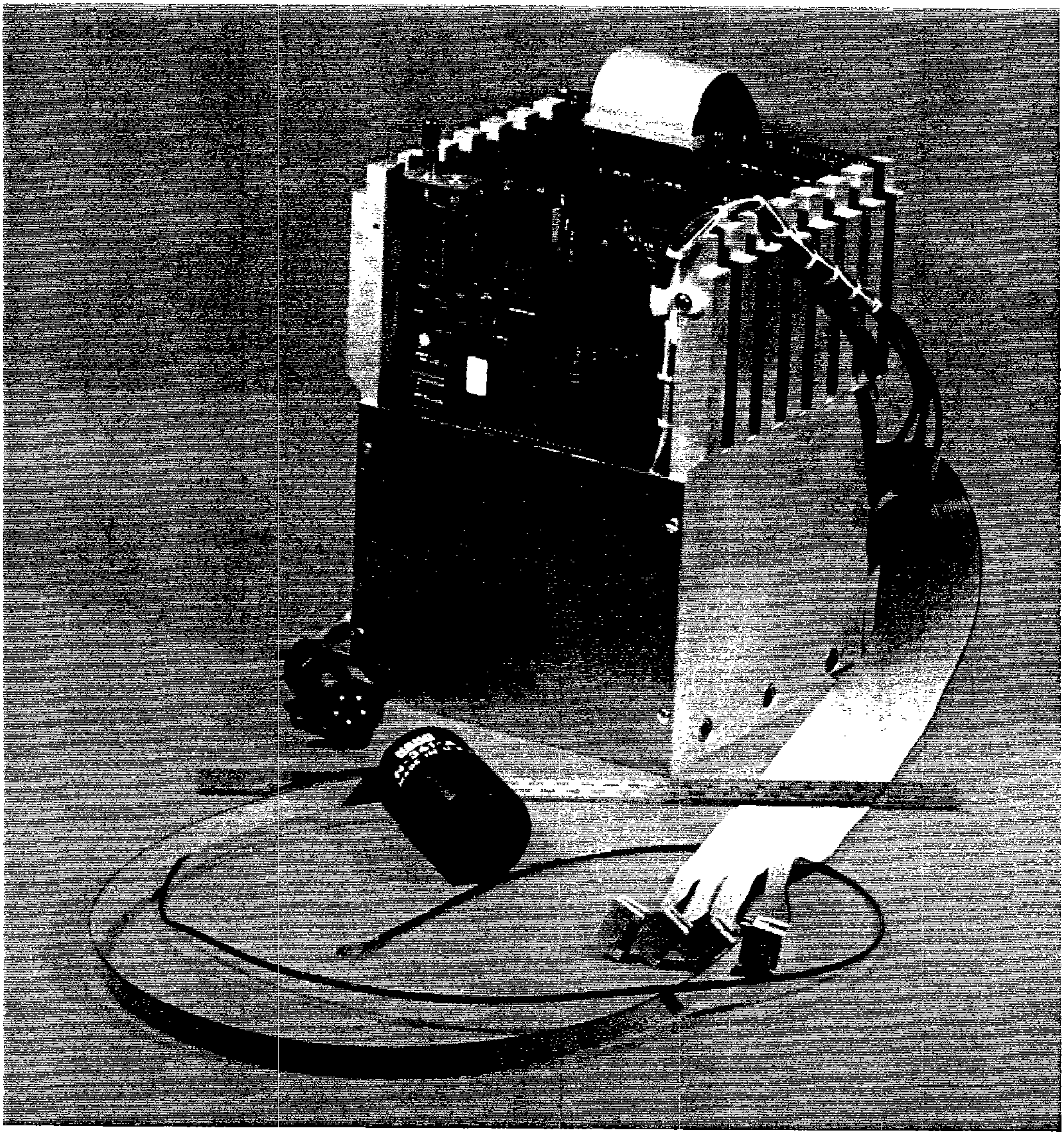


Figure 7: Photograph of a high voltage controller station. The card in the front contains the computer, Ethernet controller and EPROM. It also shows one photo-tube base plugged into an analogue card in the back.

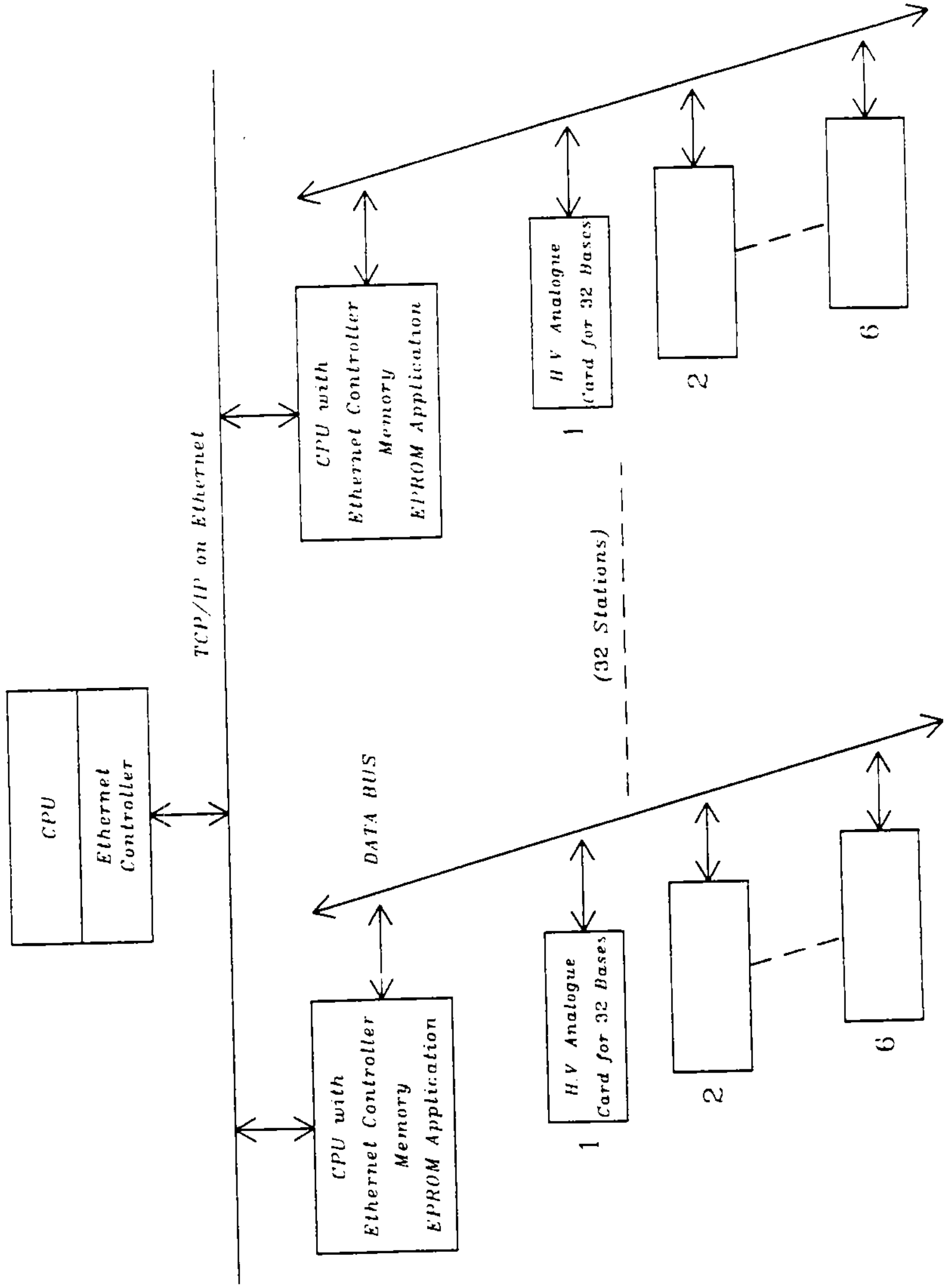
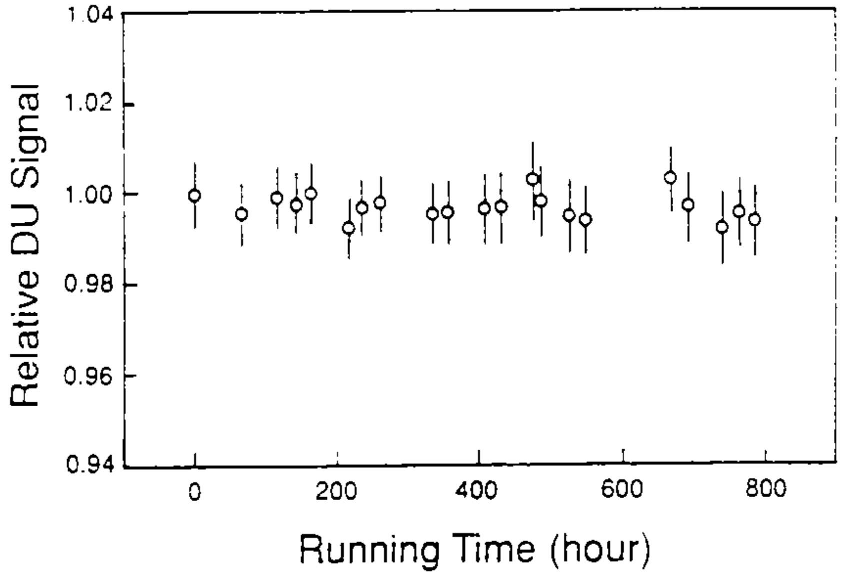


Figure 8: Schematic diagram of the Ethernet high voltage controllers for the barrel calorimeter of the ZEUS experiment at DESY.



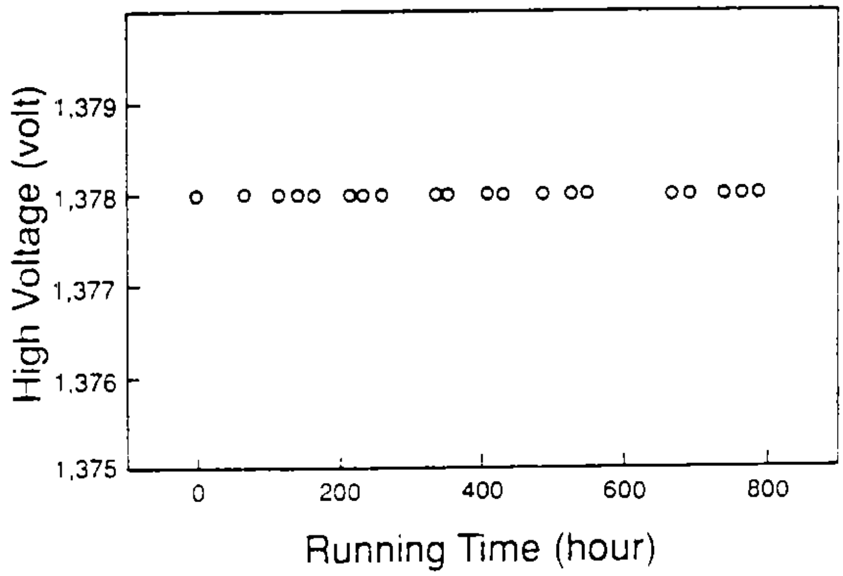


Figure 9: The top histogram shows the depleted uranium signal as a function of time. The bottom histogram shows the stability of the high voltage of one base.