SLAC-PUB-1021
(EXPI) and (ACC)
March 1972

A SURFACE-BARRIER BEAM MONITOR*

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ABSTRACT

A thin silicon surface-barrier semiconductor detector was used to monitor the intensity of a pulsed high-energy electron beam of between 10^2 and 10^6 electrons per 1.6 μsec pulse.

(Submitted to Letters to the Editors Nucl. Instr. and Meth.)

* Work supported by the U. S. Atomic Energy Commission.

I. INTRODUCTION

The SLAC machine accelerates electrons in pulses of duration 1.6 μsec at a maximum repetition rate of 360 pulses per second. Intensities approaching 10^{12} electrons per pulse at 19 GeV (or 10^{10} electrons per pulse at 22 GeV) are available. Various instruments (e.g., toroid monitors,[1] SEM's[2] and Faraday cups[3]) have been perfected for measuring the instantaneous or integrated flux for such high-intensity beams. However, an experiment[4] to study the electroproduction of hadrons required a flux of only 10^4 to 10^5 electrons per pulse. The above monitors are not useful for intensities within this range. One device which does work in this range is the quantameter[3,5] and the principal beam monitor for this experiment was the carefully calibrated quantameter described in reference 3. The disadvantages of the quantameter are its large size and its total degradation of the beam. The semiconductor beam monitor to be described is a new concept and does not suffer from these disadvantages. In addition it is extremely simple and inexpensive, it can be made absolute, it can be made sufficiently thin as to have a negligible effect on the beam properties, and it can monitor the time structure of the beam pulse as well as the integrated flux.

II. THEORY OF OPERATION

The principles of operation of semiconductor particle detectors have been exhaustively discussed elsewhere.[6,7] Basically, such a detector is just an ionization chamber consisting of a small wafer of silicon (or germanium) instead of a large volume of gas. The energy deposited in a silicon detector by the passage of a beam pulse of N electrons is equal to $N\epsilon_d$, where ϵ_d is the energy deposited by one electron. If ϵ_p is the energy required to release one ion pair in silicon, and e is the electronic charge, then the charge collected q is given by:

$$q = N\epsilon_d e/\epsilon_p. \tag{1}$$

As ϵ_p is well known to be 3.6 eV,[6,7] and ϵ_d is calculable if the detector thickness is known, then a measurement of q enables the required intensity N to be calculated. In practice, however, some care must be taken in deriving ϵ_d. Simply multiplying the detector thickness by the specific ionization -dE/dx given in the tables gives the energy lost which, for thin absorbers and high energies, is very different from the energy deposited because of the escape of delta rays. The mean ionization -dE/dx (lost) for electrons with kinetic energy E passing through matter is given by the Bethe-Bloch formula[8]

$$\frac{-dE}{dx}(\text{lost}) = \frac{2\pi ne^4}{mv^2}\left(\ln\frac{2mv^2W(E-W)}{I^2(1-\beta^2)E} - \beta^2 + \frac{W}{E-W} - \delta + \frac{W^2/2 + (2Emc^2 + m^2c^4)\ln(1-W/E)}{(E+mc^2)^2}\right) \tag{2}$$

where n=number of electrons/cc in the material, m=electron mass, v=velocity of the particle, β=v/c, I=atomic excitation potential, δ=density correction and W is the maximum energy transferable to an atomic electron in a single collision (which for an electron beam is equal to one half of the beam energy). Exact calculation of -dE/dx (deposited), sometimes referred to as "restricted stopping power" or "linear energy transfer",[9] is rather laborious. A simple approximation (good to about ±5%) can be made by replacing W in equation (2) by W', where W' is the maximum energy lost by a delta ray in traversing the radius of the detector (since delta rays emerge at almost 90^o to the beam direction). This approximation neglects the contribution from all delta rays with energies greater than W' and also ignores the fact that many delta rays will be scattered out of the thin detector. The corrections for these two effects will have opposite signs. For a 20 GeV electron and a silicon counter of depletion depth 100 microns and radius 2.8 mm, we obtain $\epsilon_d = 36.2$ keV by this method, whereas the total energy lost by ionization is 53.4 keV. Of the relatively large amount of energy lost by radiation, only a negligible fraction is actually reabsorbed in the 0.001 radiation length detector.

III. DESCRIPTION OF MONITOR

The ORTEC transmission-mounted partially-depleted silicon surface-barrier detector with 25 mm^2 of active area and a nominal 100 micron depletion layer was operated at room temperature and pressure in conjunction with the electronics illustrated in Fig. 1. Assuming a flux N of 10^2 $[10^6]$ electrons per pulse, then substituting into equation (1) gives a charge per pulse q of:

$$q = 10^2 \, [10^6] \times (36.2 \times 10^3) \times (1.6 \times 10^{-19})/3.6$$

$$= 1.6 \times 10^{-13} \, [1.6 \times 10^{-9}] \text{ coulombs per pulse.}$$

The preamplifier designed to drive the 50 Ω cable between the experimental area and the counting room was made current-sensitive rather than charge-sensitive so that the precise time-structure of the beam pulse could be observed. (For fluxes of less than 10^2 particles per pulse, a charge-sensitive preamplifier would be more suitable.) For a 1.6 μsec wide beam pulse we therefore obtain a current pulse of amplitude 1.0×10^{-7} $[1.0 \times 10^{-3}]$ amps. The input impedance and the gain of the preamplifier were chosen to be 1 K and 10 respectively, thereby producing an output pulse of amplitude 1 mV [10 V]. This pulse could be displayed on oscilloscopes for the benefit of both the experimenter and the accelerator operator, and could be integrated and digitized so as to give the accumulated electron count. Also, a repetition-rate-independent integrating sample-and-hold circuit was designed by means of which the actual intensity N was displayed on a meter with selectable full scale deflections of 1 K, 2.5 K, 10 K, 25 K, 100 K, 250 K and 1 M electrons per pulse.

IV. PERFORMANCE

Saturation

It is interesting to note that for an intensity N of 10^6 electrons per pulse, the actual energy being dumped into the detector per 1.6 μsec pulse is 36 GeV. As far as is known, never before have semiconductor detectors been required to measure such large bursts of energy, and possible saturation problems were envisaged. Within the accuracy of our measurements, no such effects have been observed.

Radiation Damage

It is well known that the resolution of silicon detectors begins to deteriorate when their exposure to minimum ionizing particles exceeds about 10^{12} particles per cm^2. In this application, however, we are very insensitive to the detector resolution and have observed no change in performance after subjecting the detector to about 2×10^{12} electrons within a beam spot size of about 4 mm^2. (We are hoping to reach 10^{13}.)

Linearity, Stability and Dynamic Range

The calibration of the monitor relative to the quantameter was linear to about ±2% between 10^3 and 10^6 electrons per pulse, and remained constant to ± 1% over a period of several months.

Absolute Calibration

Since our detector was of the partially depleted type, the calculated depletion depth of 100 microns (and hence ϵ_d) can be relied upon to only about ±10%.

Agreement between calculated and measured response was within these limits. However, totally depleted detectors are available in which the depletion depth, being equal to the actual detector thickness, can be measured quite accurately. In fact for about $400, a 100 micron 'planar' detector[7] can be obtained the thickness of which is guaranteed to ±1%. There is every reason to believe that the absolute calibration of such a device could be reliably calculated to ±2%.

Multiple Scattering

The thickness of the silicon detector used was somewhat greater than 100 microns (=23 milligrams$\cdot$cm^{-2} = 0.0010 radiation lengths). Should even this small amount of material prove excessive, detectors are available as thin as 10 microns.[7]

V. CONCLUSION

In conclusion, an extremely small, inexpensive and simple beam intensity monitor has been designed and tested at SLAC capable of ±2% relative accuracy between 10^3 and 10^6 electrons per pulse. Several crude versions of the many possible read-out techniques have been demonstrated. The detector thickness of 0.1% radiation length causes very little multiple scattering although even thinner detectors are available. It is speculated that the absolute accuracy of ±10% could be reduced to ±2% by using a more suitable detector.

We are grateful to Dr. R. S. Larsen and Prof. M. L. Perl for their help and advice, and to ORTEC for the gift of the detector.

REFERENCES

1. R. S. Larsen, Report No. SLAC 63 (1966); D. A. G. Neet, Report No. SLAC 68 (1966).
2. G. W. Tautfest and H. R. Fechter, Rev. Sci. Instr. 26, 229 (1955).
3. D. E. Yount, Nucl. Instr. Methods 52, 1 (1967).
4. W. T. Toner et al., SLAC Proposal 65, Stanford Linear Accelerator Center (1970).
5. R. R. Wilson, Nucl. Instr. Methods 1, 101 (1957).
6. G. Dearnaly, AERE-R3874 (1961); G. Dearnaly and D. C. Northrop, Semiconductor Counters for Nuclear Radiations (John Wiley and Sons, N.Y., 1963).
7. ORTEC Catalog 1002 (1970), Oak Ridge, Tennessee.
8. M. J. Berger and S. M. Seltzer, NASA SP-3012 (1964).
9. See page 17 of Ref. 8, and also Attix, Roesch and Tochilin, Radiation Dosimetry (Academic Press, New York, 1968), p. 46.

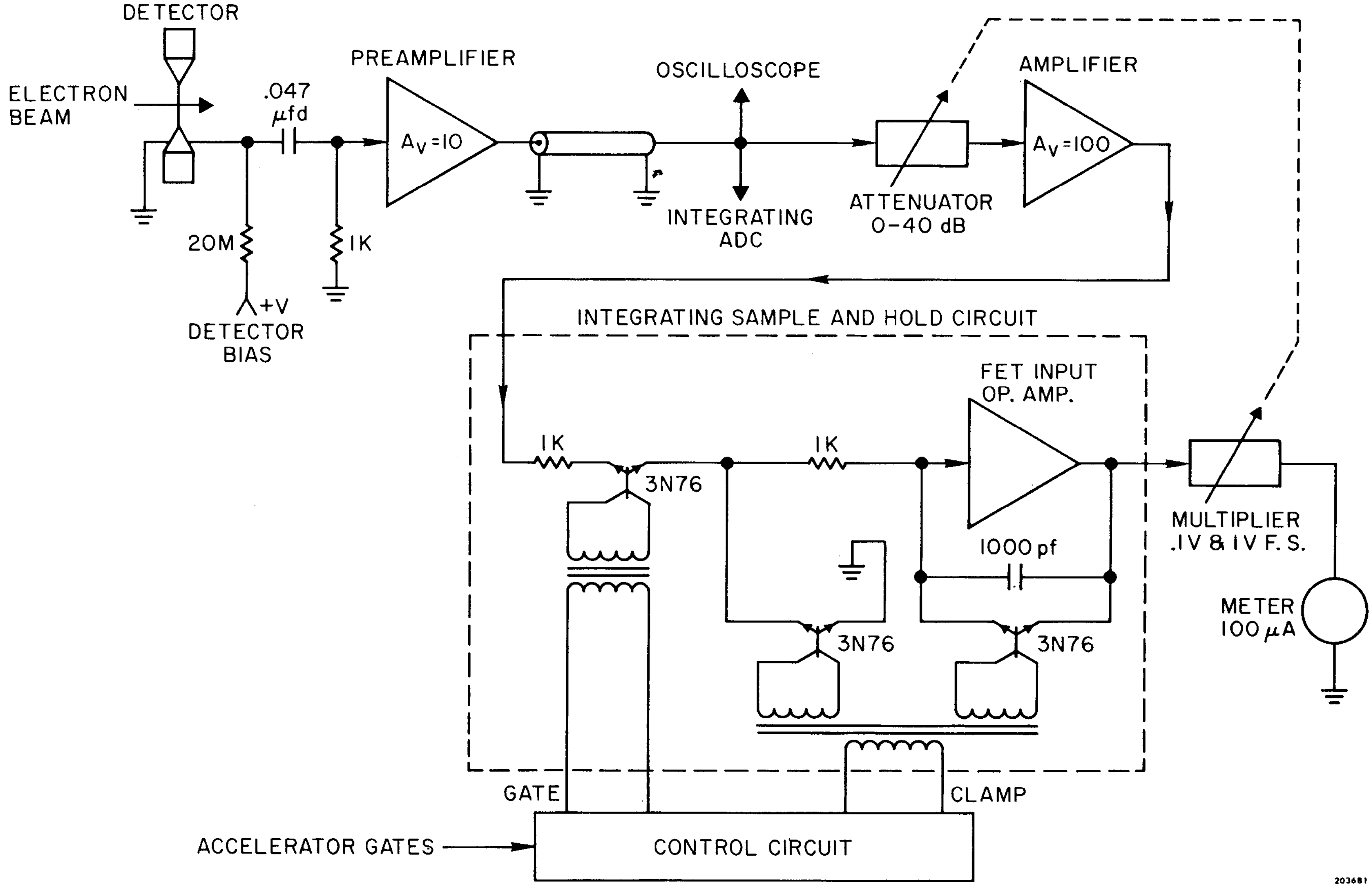

Fig. 1

Block diagram of beam monitor electronics.