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A VERSATILE HIGH RESOLUTION BEAM POSITION MONITOR*

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ABSTRACT

A new kind of Cerenkov beam position monitor is described. The counter, though relatively simple and inexpensive, has high sensitivity, introduces a minimal amount of multiple scattering, and is capable of high spatial resolution over a wide range of beam currents. Measurements of the position of the SLAC electron beam to an accuracy of ± 1/2 mm have been made for electron currents from 20 nA to 10 mA.

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I. INTRODUCTION

There are numerous situations in high energy physics where one wishes to know the position of a beam of charged particles, and correspondingly a large number of different kinds of position monitors have been developed depending on the particular application (e.g., the aperture and resolution required, the range of beam currents over which the device must be sensitive, and the amount of multiple scattering that can be tolerated). The list of references[1] is not intended to be comprehensive but rather, reviews some of the monitors which are used at SLAC and which are representative of the different kinds of devices. The performance of these devices is discussed briefly here in terms of the time structure of the SLAC electron beam (viz, a 1.6 μsec duration pulse 360 times per second). Each is basically sensitive to the total charge being measured rather than the peak current. Visual monitors such as ZnS screens or the vidicon image of the Cerenkov light from the beam are satisfactory at high currents and for displacements ≥ 1 mm but have the obvious disadvantage that at low currents, (e.g. $< 100\ \mu$A peak current), the images are no longer visible.[1a] A toroidal inductive pickup monitor, such as that described in Ref. 1b, has the marked advantage of not interfering with the beam, in addition to being simple and inexpensive. For beam currents $> 1/2$ mA it is capable of a resolution of $\sim 1/2$ mm; however, for lower currents (e.g. $\lesssim 100\ \mu$A) it is not sufficiently sensitive. Microwave position monitors are, in principle, much more sensitive. For example, one described in Ref. 1c has an 8 cm aperture and is capable of detecting a 0.10 mm beam displacement at a peak current of only 10 μA. Unfortunately, these detectors are rather complicated and expensive. A discussion of some other beam position monitors is given in Ref. 2.

The position monitor described here is a development of a counter constructed at CERN several years ago, which consisted of a triangular wedge of scintillator.[2] A similar counter has also been used recently at Serpukhov.[3] The amount of light detected when a particle passed through the counter was directly proportional to the length of the particle trajectory through the scintillator and hence also to the particle position. The present counter is based on the same idea but detects the Cerenkov light emitted in a gas rather than the light from a scintillation counter, and therefore, has the merits of small beam degradation and a larger dynamic range, in addition to good spatial resolution and high sensitivity.

The basic unit consists of two Cerenkov cells. (See Fig. 1.) The path length of a particle through one of the cells (referred to as the "flat cell") is independent of the particle's horizontal and vertical position whereas the distance which it travels through the other cell (the "wedge") is independent of its vertical position but linearly dependent upon its horizontal position. The two cells are optically separated and the light produced in each is received by separate phototubes. The ratio of the amount of Cerenkov light emitted in each cell is then a direct measure of the horizontal position of the beam and is insensitive both to the vertical position and to changes in current. A second basic unit, identical to the first but rotated 90° about the beam axis measures the vertical position of the beam. The flat cell is necessary as a normalization because of fluctuations in beam intensity.

The counter is filled with 1 atmosphere of Freon 12 for maximum sensitivity at low currents. The minimum current at which the position monitor will work effectively is limited only by the requirement that the phototube signals be integrated over a large enough number of bursts to obtain a statistically significant number of photons.[4] To achieve a position resolution of 1/2 mm, it was necessary to measure the ratio, $R=V_{wedge}/V_{flat}$, of the signals from the two phototubes to an accuracy of about 1 percent. This implies that for a Cerenkov cell consisting of 5 atm-cm of Freon and an electron burst 1.6 μsec long, the minimum current at which the position can be determined to the desired accuracy, burst by burst, is approximately 1 nA. To prevent saturation of the phototubes when operating at higher currents, the gas pressure may be decreased and/or the light entering the phototubes attenuated by means of neutral density filters or two polarizing filters. Thus the counter may be used for currents varying over at least six or seven orders of magnitude.

II. DESCRIPTION OF THE COUNTER

A. General

The two optically separated Cerenkov cells are formed by three tightly stretched pieces of 0.005 mm aluminum foil mounted within a 12 cm diameter stainless steel pipe. (See Figs. 1 and 2.) The foil does not extend all the way to the wall of the pipe so that gas may flow freely between the cells, but suitable light baffles are inserted to prevent light produced in one cell from reaching the other cell. The three foils are oriented in the following manner[5]: If a vertical plane is passed through the three foils, the lines of intersection are all parallel and the z-distance between them is therefore independent of y. (See insert, Fig. 1.) If a horizontal plane is passed through the three foils, the lines of intersection are such that as the beam is displaced horizontally the distance between planes 2 and 3 is constant, whereas the distance between planes 2 and 1 changes according to

$$\Delta z = \tan\theta \ \Delta x \quad .$$

If the z-separation between foils 2 and 1 along the central axis is z_0 and the corresponding distance between foils 2 and 3 is z_1, the ratio of the amount of Cerenkov light emitted in the wedge to that in the flat cell is

$$R = \frac{z_0 + \tan\theta\ x}{z_1}$$

and the position is given by

$$x = \frac{z_1 R - z_0}{\tan\theta}$$

B. Resolution

The accuracy to which the position can be determined clearly depends upon how well R can be measured. Any change, Δx, in the position of the beam produces a change, ΔR, which is given by

$$\Delta R = \frac{\tan\theta}{z_1}\ \Delta x$$

If there is some uncertainty in the measurement of R, there will be a corresponding uncertainty in the determination of the position. Specifically, the error in position which results from a relative error $\epsilon = \delta R/R$ in the ratio is

$$\delta x = \frac{z_1}{\tan\theta}\ \delta R = \left(\frac{z_0 + x\tan\theta}{\tan\theta}\right)\ \epsilon$$

This makes it quite apparent that the resolution is improved by increasing $\tan\theta$ and decreasing z_0, and that it is linearly dependent on x. For the particular counter tested $\theta = 65^o$, $z_0 = 7.5$ cm, and $\epsilon = \pm 1\%$ which results in an error of $\delta x = \pm .4$ mm for x=0. The uncertainty in R which limits the accuracy of the position monitor may arise from errors in construction (e.g., orientation of the foils), nonuniformity of light collection or nonlinearity in the phototube and the dividing electronics. Errors arising from the optics and electronics are discussed below; the errors in construction are minimal.

C. Optics

The optics are rather simple but it is important that the light collection efficiency be uniform as a function of the beam position — for example, to better than 1% for the counter tested. Each of the foils 2 and 3 reflects the light from its respective Cerenkov cell into a lucite light pipe which is tapered from a 5 cm diameter at one end to a 2.5 cm diameter at the other end. Since phototubes generally have a very nonuniform response as a function of the entrance position of the photons, two 3 mm thick sandblasted lucite disks diffuse the light and a lucite cone directs the light to the face of the photomultiplier tube. (See Fig. 1.) This particular combination of light pipes, diffusers, etc., was found to have a light collection efficiency uniform to ±1% within the range ±1cm about the z axis. The uniformity was measured by shining a He-Ne laser beam parallel to the z axis to simulate the Cerenkov light emitted from a beam of charged particles (but with zero "Cerenkov angle," of course).

D. Electronics

Since there were sharp fluctuations in beam intensity within a single burst, it was necessary to integrate and smooth the phototube signals. This was particularly true during the testing at low currents. The peaks of the integrated signals from each of the cells were determined with a peak-hold detector and their ratio taken with an analog divider. All three signals (i.e., the wedge output, V_{wedge}, the flat cell output, V_{flat}, and their ratio $R = V_{wedge}/V_{flat}$) may be displayed on a digital voltmeter or, alternatively, read into an analog-to-digital converter and subsequently into a computer. During the tests of this counter, the signals were recorded using an IBM Model 1800. A complete diagram of the electronics is shown in Fig. 3.

In order to avoid systematic errors, it is necessary that the ratio of the overall electronic gains for the signals from each cell be constant. Since the integrated voltage signals are given by

$$V_{wedge} = (z_0 + x \tan\theta) C\ E_1 G_1$$

$$V_{flat} = z_1 C\ E_2 G_2$$

where C = the amount of light emitted per unit path length

E_1, E_2 = the light collection efficiency for the two cells

G_1, G_2 = the overall gain of the phototubes and integrating electronics,

the measured displacement of the beam from the center axis is

$$\Delta R = \frac{\tan\theta}{z_1} \frac{E_1}{E_2} \frac{G_1}{G_2} x$$

C depends only on the index of refraction of the gas and the momentum of the particle which are the same for both cells. Therefore, given that z_1, $\tan\theta$, E_1 and E_2 are fixed constants, the measured position is proportional to $(G_2/G_1)x$.

III. MEASUREMENTS AND RESULTS

The counter was tested at SLAC in a primary electron beam consisting of ten bursts per second. In order to demonstrate the complete dynamic range of the monitor, two separate runs were made: one in which the peak beam current was varied from 100 μA to 10 mA and one in which the current was varied from 20 nA to 13 μA. For the first run, the cell gas was one atmosphere of N_2 and the Cerenkov light was attenuated by 10^4 before entering the phototubes, whereas for the latter run the gas was 1 atmosphere Freon 12 and the attenuation factor was 10^2(6). The counter was mounted on a traverse table and was aligned with the electron beam along its center axis. It was then traversed in 5 mm steps in the horizontal direction over a total range of ± 25 mm about the center position; the individual phototube signals as well as their ratio, R, were recorded.

It was observed that there was some fluctuation in the measured position from pulse to pulse, and therefore the average measurement of 10-20 pulses was taken to be the measured position of the beam. A plot of these positions versus the actual position of the traverse table for both the low and high current runs is shown in Fig. 4. The accuracy with which the beam position can be measured was found to be $\pm 1/2$ mm over the entire current range.

The approximate standard deviations (σ_{pulse}) of the pulse-to-pulse position measurements are also given in Fig. 4 for each current. These fluctuations, which are approximately 3/4 - 1-1/2 mm for the high currents and 1/4 - 3/4 mm for the lower currents, could have been produced by statistical fluctuations in the amount of background light, by sensitivity of the electronics to such factors as beam pulse shape or by actual changes in beam position.[7] We believe that the variations were produced by real movement of the beam, since such movement was visually observed at high beam currents on a Zns screen. However, this correlation was not quantitatively verified.

IV. CONCLUSION

In conclusion, a simple and inexpensive beam position monitor has been designed and tested at SLAC which is capable of measurement of the spatial position of the accelerator beam to an accuracy of $\pm 1/2$ mm over a range of 10^6 in beam currents. This sensitivity is maintained down to a few nanoamps. The total material presented to the beam is 0.3% radiation lengths and consequently the multiple scattering is minimal. The counter is readily suited to interface to a digital computer and makes for ideal beam control instrumentation.

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REFERENCES AND FOOTNOTES

1. a. R. W. Coombes and D. Neet, IEEE Transactions on Nuclear Science NS14, 1111 (June 1967).

   b. L. Johnston et al., IEEE Transactions on Nuclear Science NS14, 1106 (June 1967).

   c. E.V. Farinholt, Z.D. Farbas, and H. A. Hogg, IEEE Transactions on Nuclear Science NS14, 1127 (June 1967).

2. D.W.G.S. Leith, Nucl. Instr. Methods 25, 224 (1964).

3. S. V. Donskov, Yu. D. Prokoshkin, R. S. Shuvalov, IHEP preprint No. IFVE-68-22K (1968).

4. At a synchrotron it would only be necessary to integrate over a fraction of a beam burst, since the duration of the burst is approximately 10^5 times that of the SLAC beam.

5. The description given is for the unit which measures the horizontal position. As mentioned in the text the unit which measures the vertical position is identical but rotated 90° about the longitudinal axis of the counter. The exact orientation of the foils is produced as follows: Consider the right-handed coordinate system defined as having the z axis along the beam direction and the y axis vertical. Then the orientation of foils 3 and 2 (see insert, Fig. 1) is obtained simply by rotating a foil which initially lies in the xy plane by 45° about the x axis. Foil 1 is obtained by again beginning with a foil lying in the 45° plane as 2 and 3 and rotating it about the y axis, at the same time maintaining the 45° inclination. The resulting orientation of the three foils has the desired properties mentioned in Section II.A.

6. It should be noted that spurious light may be produced by stray particles emitting Cerenkov radiation in the lucite pipes. By measuring the phototube outputs when the counter was evacuated, it was determined that the amount of background light produced in this way was sufficiently large, during the high current run, to lower slightly the effective resolution of the counter. For this reason, it is probably advantageous to design the counter with air light guides rather than with lucite ones.

7. Larger fluctuations of 2-3 mm occurred for $I \approx 20$ nA since, at this low current, photon statistics began to be important. However, during this run the light entering the phototube was still attenuated by 10^2. With these remaining filters removed, the effect of photon statistics should be negligible for currents > 1 nA.

FIGURE CAPTIONS

1. A projective drawing of the beam position monitor showing the two units which measure the horizontal and vertical position. Note that the phototube and light guide assembly for the vertical unit is omitted in the drawing for simplicity. The insert shows the vertical and horizontal cross sections of the three foils which define the Cerenkov cells of the horizontal unit.
2. Photograph of the counter described.
3. Diagram showing the electronics for determining the ratio R.
4. The measured position, $R = V_{wedge}/V_{flat}$, is plotted versus the actual position of the traverse table for each of the currents at which the counter was tested; the errors are less than the point size. The straight line is drawn by eye. No attempt was made during the test run to adjust the phototube gains so that the calibration would be the same at each current. Hence the difference in the slopes of the lines at different currents.

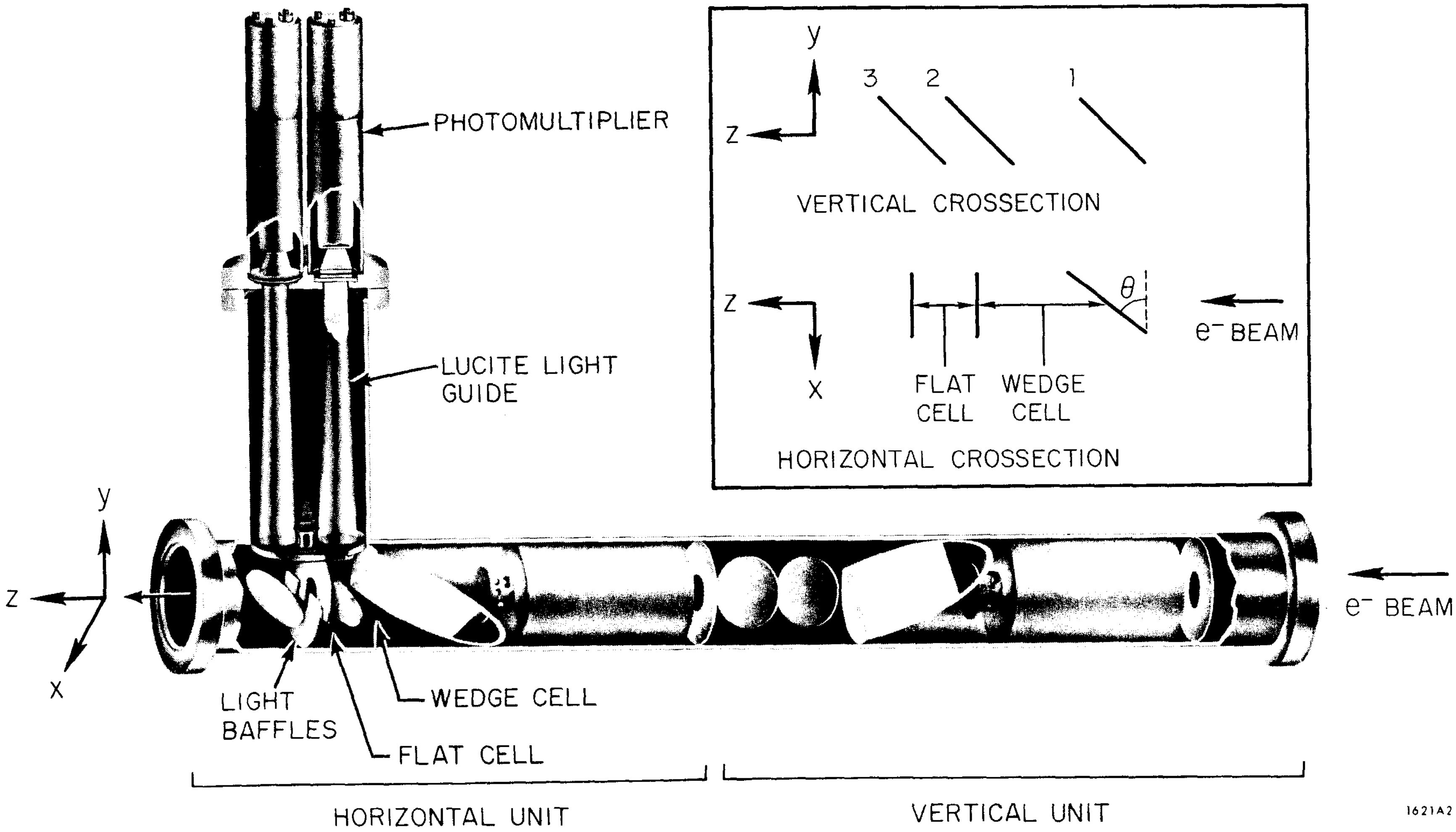
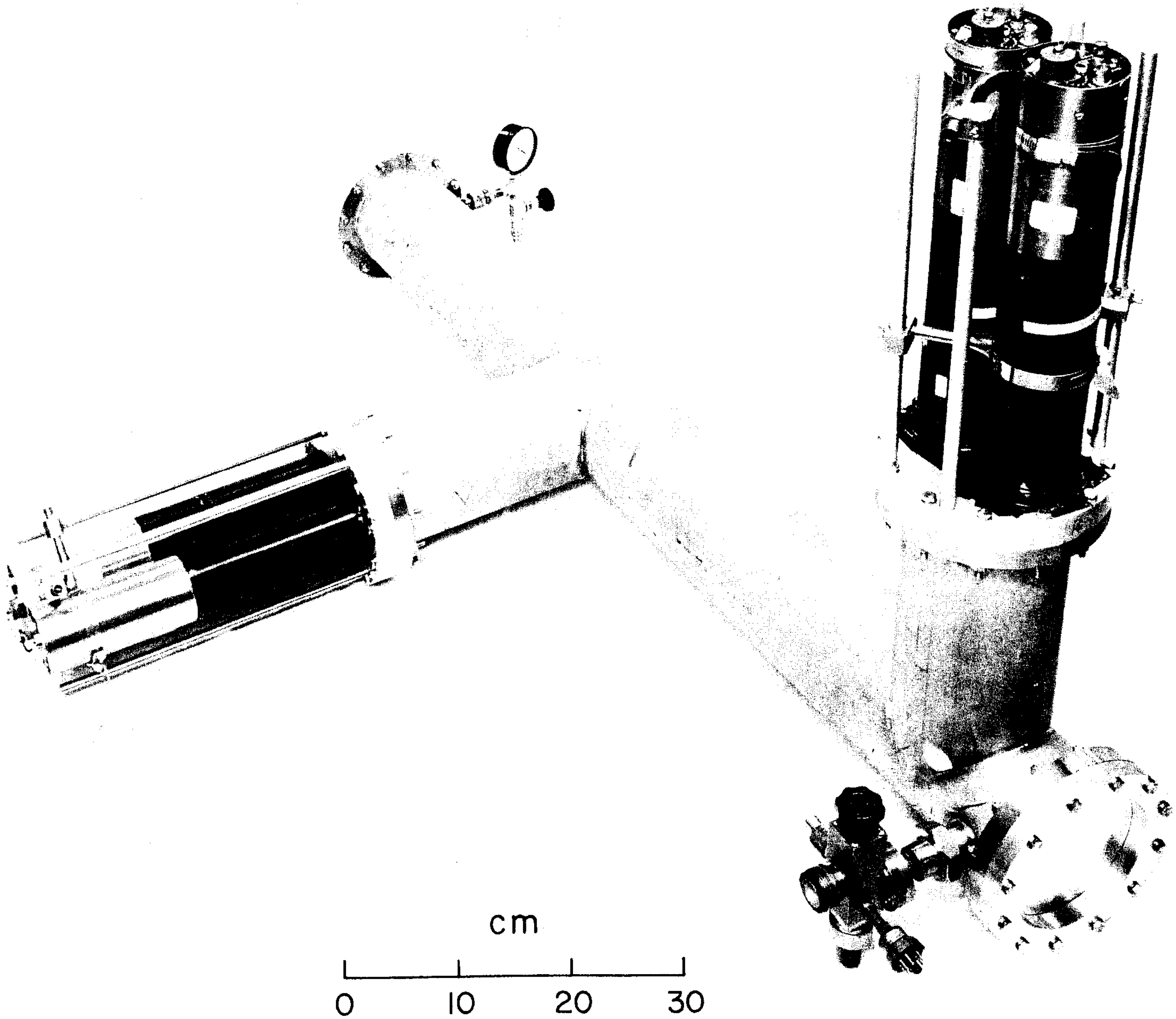
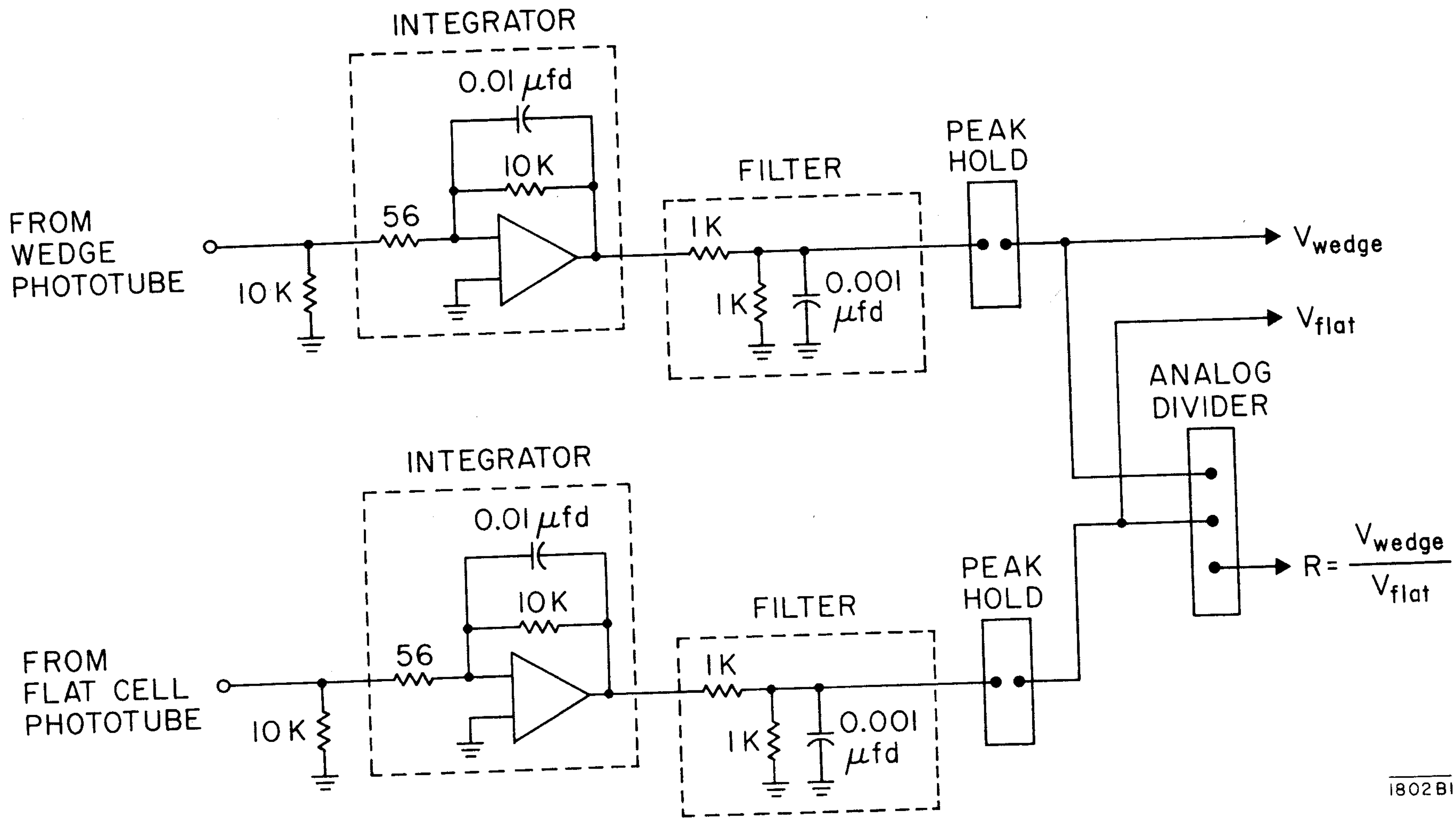

PHOTOMULTIPLIER
LUCITE LIGHT GUIDE
y
z
x
LIGHT BAFFLES
WEDGE CELL
FLAT CELL
e⁻ BEAM
HORIZONTAL UNIT
VERTICAL UNIT
y
3
2
1
z
VERTICAL CROSSECTION
z
x
θ
e⁻ BEAM
FLAT CELL
WEDGE CELL
HORIZONTAL CROSSECTION
1621A2

Fig. 1



1802A4

Fig. 2


INTEGRATOR
0.01 μfd
10K
56
FROM
WEDGE
PHOTOTUBE
10 K
FILTER
1K
1K
0.001
μfd
PEAK
HOLD
V wedge
V flat
ANALOG
DIVIDER
R = V wedge / V flat
INTEGRATOR
0.01 μfd
10K
56
FROM
FLAT CELL
PHOTOTUBE
10 K
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PEAK
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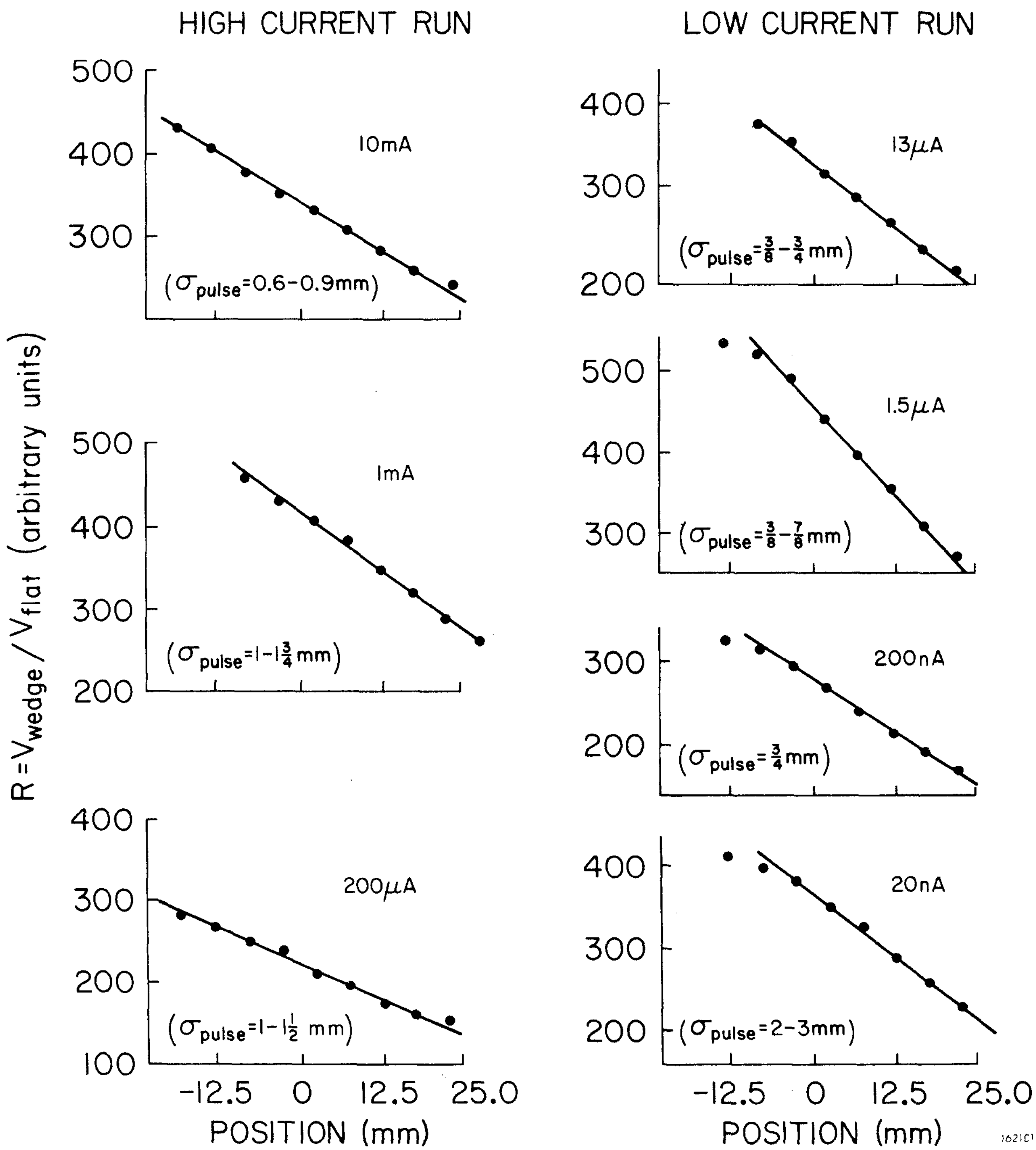
1802B1

Fig. 3



HIGH CURRENT RUN
LOW CURRENT RUN
R = V_wedge / V_flat (arbitrary units)
10mA
(σ_pulse=0.6–0.9mm)
1mA
(σ_pulse=1–1¾ mm)
200μA
(σ_pulse=1–1½ mm)
13μA
(σ_pulse=⅜–¾ mm)
1.5μA
(σ_pulse=⅜–⅞ mm)
200nA
(σ_pulse=¾ mm)
20nA
(σ_pulse=2–3mm)
100
200
300
400
500
−12.5
0
12.5
25.0
POSITION (mm)
1621C1

Fig. 4