MAY 31 1968

CEAL- 1040

~~CONF-680430--1~~
CONF-680427--5

CALIBRATION AND PERFORMANCE
OF CEA QUANTAMETERS

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May 1, 1968

This paper was presented at the Symposium
on Beam Intensity Measurement held at the
Daresbury Nuclear Physics Laboratory,
Daresbury, England, April 22-26, 1968

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The research work described in
this report was performed under
Contract AT(30-1)-2076 between
the U.S. Atomic Energy Commission
and the President and Fellows of
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CEAL-1040

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May 1, 1968

CALIBRATION AND PERFORMANCE OF CEA QUANTAMETERS*Introduction

The high-energy photon beams used for experimental purposes at the Cambridge Electron Accelerator are monitored at present with gas-filled quantameters of the type first proposed by R. R. Wilson¹. With the exception mentioned below, they all have the same mechanical characteristics and have already been described elsewhere² (see Fig. 1). Suffice it to state that the photon-induced shower is developed and absorbed in 18 unplated, 1-cm thick, copper discs totalling $12.5 X_0$ and having a useable, uniform, 6.2-in. diameter free of mechanical supports. It has been experimentally determined³, by measurements of the total number of ions collected for each incident electron (and hence photon), that this configuration ensures the linearity of response throughout the energy range at CEA.

*During periods ending December 1967. The information contained in this report covers time intervals varying in each case according to construction and filling dates, but is mainly meant to provide a uniform record since operations were resumed at CEA after the explosion of July 5, 1965.

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The quantameters were filled with one of two gas mixtures:

- (a) A(94%) + CO₂ (6%), mainly for purposes of intercalibration with other laboratories having adopted the same gas mixture originally chosen by Wilson (two units), and
- (b) He (90%) + N₂ (10%), for purposes of reducing saturation and recombination phenomena as determined in earlier measurements² (three units). The condition of these quantameters has not been altered in any way since they were initially filled at a slightly positive pressure a few years ago.

In order to reduce undesirable intensity-dependent saturation effects* observed with standard quantameters, the construction of one quantameter (Q1B) has been modified to reduce the gap between plates. All gaps were made equal (unlike the alternate 1 mm and 2 mm in the Wilson version), and the average spacing thus became 0.50 mm. The total copper thickness was reduced to 17.15 cm and the "compensating gap" to 2.14 mm. Because of this structure the electric field for a given voltage between plates is different from that in the other CEA quantameters.

In addition to these five gas-filled quantameters, two other units (Q1A, with unplated discs; Q1D, with gold-plated discs) were evacuated for use as nonsaturable secondary emission quantameters.^{4,5,6} To date the photon beam intensities available at CEA have never exceeded levels necessitating their use.

*In what follows, saturation refers to departure from linearity of response with beam intensity.

The energy content of a photon beam is given¹ by:

$$U = \frac{wr}{e} q = U_q \cdot q$$

where q is the charge collected, w the energy loss per ion pair for the gas mixture, r the ratio of energy loss in copper to the energy loss in the gas, e the electron charge and U_q the quantameter constant. The ratio r has the form:

$$r = a \frac{\rho_{Cu} t_{Cu}}{\rho_{gas} t_{gas}}$$

where ρ is the density, t the thickness, and a a constant depending on the average relative ionization losses in copper and the gas mixture.¹ For a given quantameter and a given gas mixture, the calibration constant U_q thus depends only on p/T .

The ratio p/T has been recorded periodically and is given for each quantameter (Figs. 11-15). Short of an actual calibration as described below, this ratio represents a satisfactory stability check.

The gas pressure in all five quantameters under discussion remained unchanged to within about $\pm 1.5\%$ throughout the period covered by this report. Pressure decreases below atmospheric previously reported² for two quantameters are now explained by slowly developing, probably radiation-induced porosities in the vacuum enclosure. These enclosures were replaced with new ones made of Type 321 stainless steel.

Calibration and Performance

All measurements were made in runs with an external electron beam of accurately known energy⁷ ($\pm 0.2\%$). The quantameter response was calibrated against a Faraday cup (taken to be an ultimate standard) by an intermediate monitor.

The Faraday cup (No. 1) was designed^{2,8} to collect the beam charge to better than 99.9% by absorbing the shower developed therein by an incident electron. However, the charge collected in the cup may also depend upon the overall characteristics of the particular beam run in which it is located. Although it was not designed for this purpose, an attempt was made to use the Faraday cup itself as a calorimeter, but it proved unsatisfactory because the thermal insulation was insufficient.⁹ An absolute calibration, in which the actual output of the Faraday cup is compared directly to the incident electron beam by a null method¹⁰, indicated the efficiency to be $99.2 \pm 0.4\%$ at 3 GeV. However, due to difficulties with beam jitter for short spill lengths (50-60 μsec) and intensities insufficient for best use of this method, this measurement is preliminary and a value of 100% was adopted throughout this report.

The integrators used in all measurements operate as follows: the input charge is integrated by a Miller amplifier, the output of which at a certain level triggers a discriminator which in turn actuates a relay enabling a known charge

of opposite polarity to be fed from a reference capacitor to the amplifier input.¹¹ The overall accuracy and stability of these integrators are better than 0.3% for the ranges 10^{-5} - 10^{-8} Coul. and 0.5% for the range 10^{-9} Coul. They were periodically calibrated by adjusting the discriminator to levels known to within at least 0.1%.

The intermediate monitor was a thin, nonsaturable secondary emission monitor (SEM) similar in construction to that used in earlier measurements.² It consists of 9 goldplated (1000 Å per surface) Al foils 0.0003" thick supported on 10.5" I.D. rings. The entire assembly is enclosed in a vacuum container having two 0.003" stainless steel windows. The total thickness of this monitor is thus $1.0 \times 10^{-2} X_0$. A titanium-discharge, 8 l/sec Drivac pump is permanently incorporated, and the monitor has been under continuous vacuum ($p \leq 3 \times 10^{-8}$ torr) since construction was completed in April, 1966.*

If the electron beam is of energy E, the quantameter constant U_q obtained by replacing the quantameter with the Faraday cup, is then given by the expression:

$$U_q = \frac{E}{e} \frac{(q_{FC}/q_{SEM})}{(q_Q/q_{SEM})}$$

where q_{FC} , q_{SEM} and q_Q are the charges collected in the Faraday cup, the secondary emission monitor and the quantameter respectively. U_q is usually expressed in MeV/Coulomb.

*Prior to this date, calibrations were made with a smaller (5.5" I.D) goldplated, intermediate monitor of similar construction and also continuously kept under vacuum.

The experimental setup is shown in Fig. 2. The electron-beam transport system, upstream from the exit window (0.002" stainless steel), is evacuated to pressures below 1μ and includes an intermediate 0.002" Al window. The matter in the beam run upstream from the quantameter (including all windows, SEM and a 28-ft air path) amounts to a total of $4.5 \times 10^{-2} X_0$.

All quantameters were biased at +400 V, a value chosen from earlier measurements to be the middle of the ion collection plateau. All calibrations were made at this level. In the case of Q1B, for which the middle of the plateau is +200 V, calibrations were made for both biases. The ion collection curve for Q1B is shown in Fig. 3.

In order to identify and properly interpret the observed saturation effects discussed below, the intensity dependence of the intermediate SEM response in a 3 GeV electron beam (approximate cross-sectional area $0.4 - 0.6 \text{ cm}^2$) was measured and is given in Fig. 4, assuming the Faraday cup response to be independent of beam intensity. It is seen that, except for very low currents where both integrators are operated in the less accurate 10^{-9} Coul. range as described above, there is no saturation to within less than 1% for average beam intensities of 0.5 to 50 nA (or 5.2×10^7 el/pulse to 5.2×10^9 el/pulse respectively), the range within which quantameter calibrations are carried out. The response of this monitor, biased at -1 kV, was also measured to be independent within 0.5% of beam distance from its axis (up to 3 in.).

Because the ion collection between the plates involves recombination and other secondary effects, the saturation of a quantameter for a given gas mixture depends primarily on spill length and total beam intensity.² A test made during the present measurements (with the more sensitive A - CO₂ mixture) showed that, for a given spill length and normally available duty cycle of 25 - 50% within it, the saturation curve is independent of this duty cycle (Fig. 9).

Saturation curves were obtained for all quantameters with beam spill lengths of about 100 μ sec and 500 μ sec (these being the routine limits for normal operation of the CEA). They are shown in Figs. 5 - 9 as a function of both the incident electron beam intensity and the quantameter output. It can be seen from these curves that for both mixtures the difference in saturation associated with short and long spill lengths increases with incident beam intensity. The sensitivity of quantameters filled with the A (94%) + CO₂ (6%) mixture is about 6.3 times higher than when filled with the He (90%) + N₂ (10%) mixture, in agreement with earlier measurements.² In comparing the saturation characteristics of the two gases, we note that, for a given incident electron beam intensity (e.g. 12 nA), the saturation effects in one gas mixture for two spill lengths are in the same ratio (about 3.0) as in the other gas mixture. Similarly, for a given incident beam and the same spill length, the saturation

effects in the two gases are also approximately in the same ratio (about 7.2). The lack of uniformity for certain points is due to instabilities in synchrotron operation, mainly in the control of beam intensity, beam extraction and spill length.

It should be noted that the saturation curves for both gas mixtures and both spill lengths exhibit a common trend toward decrease in saturation at high beam intensities. This trend is compatible with the establishment of an equilibrium between ionization, recombination, and multiplication processes.

For the modified quantameter Q1B, saturation curves were taken at biases of both +200 V and +400 V (Fig. 5). It is clear that, as expected because of reduced gas volume, differences in saturation for the same spill lengths as above are greatly reduced in comparison with the standard case. For the +200 V bias (middle of plateau) the saturation is almost independent of spill length for output currents up to 8 - 10 μ A. The more pronounced dependence of saturation on beam intensities for this case (as compared to + 400 V) can be attributed to the fact that the drift velocity is smaller, with reduced electric field between plates, and hence the incidence of ion recombination, attachment and other secondary processes becomes larger. The collection time (about 10 μ sec) is much shorter than the shortest spill length and therefore ions are subjected to the radiation throughout the gap width. For small beam intensities, recombination of ions is predominant, which results

in a net loss of charge. As the beam intensity increases, the molecules recombined at an early stage of drift may again be ionized in the radiation field and contribute to the collected charge, thus reducing saturation.

The quantameter constant U_q is always quoted for very small beam intensities for which there is almost no difference between saturation curves.

In comparing the standard and the reduced-gap quantameters, after normalizing for the same $p/T = 2.64$ mm Hg/°K, we note that their sensitivities are in the ratio:

$$\frac{U_q(Q1G, 2.64)}{U_q(Q1B, 2.64)} = 4.1$$

whereas their average spacings are in the ratio 3.0. The discrepancy comes from the fact that the thickness of the plates is slightly different for the two quantameters and that the gas-filled gaps intercept different portions of the shower.

Beam runs and experimental conditions in high-energy photon experiments usually vary within certain ranges. To assess the consequence of such modifications on quantameter response and hence on the interpretation of scattering or photo-production data, calibration measurements were also obtained as a function of absorber of thickness t located between the SEM and the quantameter. The quantameter and SEM responses remain unchanged and therefore this implies that the fraction of the shower induced by the absorber is completely absorbed

in the quantameter together with the main shower (Fig. 10a). That the SEM response remains unchanged in this case is also shown by the value of the ratio q_{FC}/q_{SEM} (Fig. 10b). Assuming that the Faraday cup response is not modified by shower developed immediately upstream, the very small decrease in this ratio for larger amounts of matter in the beam could be due to loss of charge from the Faraday cup or to increased secondary emission in the foils caused by back scattering from the absorber. This case, however, shows an increase in "total spread" of the Faraday cup response with increased absorber thickness. The "spread" is a relative broadening of Faraday cup response when biased at ± 1 kV, the meaning of which, although most likely attributable to phenomena caused by low-energy photons from the degraded shower and by low-energy particles in the beam halo, still remains uncertain, but has been nevertheless used as a criterion for beam "cleanliness". When the absorber is located in front of the SEM, the ratio q_Q/q_{SEM} decreases substantially with increasing absorber thickness. This behavior can be explained by the fact that in this case secondary electrons are emitted from the foils by both members of an $e^+ - e^-$ pair created in the absorber.

The quantameter calibrations were repeated in the same experimental setup at different time intervals from the initial filling (between December 1964 and March 1966) until December 22, 1967. The stability in time for U_Q for all quantameters during

this period, together with the corresponding value of p/T , is shown in Figs. 11 - 15. It appears that, for all quantameters during the period under discussion, the value of p/T exhibits a small increase of the order of 1%. This feature is not sufficient to alter substantially the quantameter constant as shown by the actual calibrations. It is most likely due to a very slow diffusion of gas from the atmosphere. It should be mentioned that during this period the stability in accelerator performance, together with the understanding of experimental uncertainties have steadily improved. The later calibrations should therefore be considered as more systematic and reliable.

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FIG. 1 - QUANTAMETER STRUCTURE

FIG. 2 - EXPERIMENTAL SETUP

FIG. 3 - ION COLLECTION CURVE for QUANTAMETER QIB

FIG. 4 - DEPENDENCE of SEM 4 RESPONSE
ON BEAM INTENSITY

FIG. 5a - SATURATION CURVES
FOR QUANTAMETER Q 1B (+200V)

FIG. 5b - SATURATION CURVES
 FOR QUANTAMETER Q1B (+400V)

FIG. 6 - SATURATION CURVES FOR QUANTAMETER Q1C

FIG. 7 - SATURATION CURVES FOR QUANTAMETER Q1E

FIG. 8- SATURATION CURVES FOR QUANTAMETER Q1F

FIG. 9 - SATURATION CURVES FOR QUANTAMETER

Q1G

FIG. 10- DEPENDENCE OF MONITOR RESPONSE
ON ABSORBER IN THE BEAM

FIG II - TIME DEPENDENCE OF P/T AND U_q FOR QUANTAMETER Q1B

FIG 12 - TIME DEPENDENCE OF p/T AND u_q FOR QUANTAMETER Q1C

FIG. 13 - TIME DEPENDENCE OF P/T AND U_q FOR QUANTAMETER Q1E

FIG 14 - TIME DEPENDENCE OF p/T AND u_q FOR QUANTAMETER Q1F

FIG 15 - TIME DEPENDENCE OF P/T AND u_q FOR QUANTAMETER Q1G

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