DETECTION OF LOW ENERGY PARTICLES

A STUDY OF THE DETECTION OF LOW ENERGY ELECTRONS AND ATOMIC PARTICLES

by

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ABSTRACT

The channel electron multiplier is a radiation detector suitable for the detection of 0.1-100 keV electrons and atomic particles. Studies were made to determine channeltron absolute efficiency as a function of input particle rate, time, and incident energy. The efficiency for electrons was found to vary from 90% for 1 keV electrons to 50% for 4 keV electrons. The channeltron efficiency was found to depend strongly on input rate below 50 counts per second. Although the cause of this discrepency is unclear, a possible explanation was developed involving the secondary emission coefficient of the detector multiplying surface.

The channeltron was subsequently used to detect secondary electrons from gold foil bombarded with both electrons and protons. By scattering the incident particles from a gold foil, the number of secondary electrons generated was found to vary linearly with energy from 2 to 11 keV. The possibility exists for use of the foil-channeltron detector to count neutral atomic particles with known efficiency. This has been a difficult problem in the past.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The channel electron multiplier (CEM or channeltron) is a glass tube with a large length to diameter ratio, the inside of which is coated with a resistive electron multiplying surface. This surface acts as a continuous dynode when a voltage is applied over the length of the tube. An ionizing particle which is incident on the input end of the tube causes secondary electrons to be emitted which in turn are mutiplied.

The channeltron has been in use for many years but its operational characteristics are still not well understood. Advantages of the CEM include windowless operation avoiding the problem encountered by conventional detectors in which low energy radiation connot penetrate the shielding material. The CEM is replacing electrometers and discrete dynode electron mutipliers because of its reported high detection efficiency for charged particles in the range 100 eV to 400 keV. Gains of 10^9 are possible permitting the counting of individual particles.

The detection of low energy electrons and atomic particles has been hampered by the lack of an efficient sensing device capable of yielding reproducable quantitative results. This study is a continuation of work initiated to facilitate experimentation in two particular areas:(1,2) neutron radiography and the study of the interaction of ions and neutral particles with materials.

1.1 Areas of Application Requiring the Use of Channeltrons

1.1.1 Neutron Radiography

In neutron radiography, images result from the differential attenuation of neutrons by different nuclides in a specimen. The transmitted neutrons produce internal conversion electrons in a converter, typically Gadolinium. These electrons then darken photographic film to produce the image.

The energy spectrum of the internal conversion electrons is of prime importance for the optimization of the converter to give the maximum electron to neutron ratio. The unavailabitity of data relating channeltron counting efficiency to electron energy has made experimental determination of an energy spectrum impossible. Efficiency is the single most important parameter involved since efficiency variations result in more data loss than corresponding changes in CEM gain.(3)

In this report, the absolute detection efficiency for electrons is found as a function of both energy and input current. Channeltron time dependent effects are also examined. A simple model is proposed relating CEM efficiency to input rate.

1.1.2 Atomic Particle Interaction Studies

In the development of a controlled fusion reactor, one of the major considerations is the way in which the plasma will interact with the confinement vessel. Of particular interest are scattering phenomena and the mechanisms of radiation damage to solids. For proposed D-T reactors, ion energies of 100 eV to 30 keV are expected. Scattering interactions in this range induce backscattered particles which are 80% neutral. The experimental observation of these neutrals, as well as the ions, has been difficult because of uncertainties concerning detector performance. Further complications arise because the channeltron detects different charge states of the same particle with different efficiencies.

1.2 Linear Efficiency Particle Detector

A secondary emission type detector is built and tested which has linear efficiency from at least four to eleven kilovolts for incident protons. It is expected that this arrangement can be used to detect neutrals with a similar linear response. The linear efficiency versus energy makes the unfolding of experimental energy spectra very easy, when compared to the situation for directly counted particles.(4) In addition, the dependence of efficiency on charge state is also reduced for the foil-channeltron detector.

2. APPARATUS

The channeltron used in this experiment was a Mullard B312BL with a rectangular input cone of 3 mm by 10 mm. This type of channeltron is coiled to stop positive ion feedback.

The absolute detection efficiency is defined as the percentage of input particles producing a channeltron output pulse. The error in any efficiency measurement will be at least as large as the error in the input current determination. Typically maximum permissible input rates are 10^4 to 10^5 counts per second. This corresponds to an input current of

$$10^{4(5)} \frac{\text{electrons}}{\text{s}} \times \frac{1 \text{ Coul}}{6.2 \times 10^{18} \text{ electrons}}$$

or

$$I_{\text{in max}} = 2 \times 10^{-15(-14)} \text{ Amp.}$$

Direct measurement of such small currents was impossible, so a larger current was measured using a Keithley 417 picoammeter and the beam was geometrically attenuated by a known amount. Figure 1 shows the aperature assembly used to infer what the current entering the channeltron was. The first hole of 1.59 mm diameter defined the beam size. The beam was collected for measurement in a Faraday cup which was unbiased to eleminate leakage current problems through insulators. A 10 µm aperature in the Faraday cup passed a small fraction of the beam onto the channeltron. The bias plates before and after the Faraday cup were used to suppress secondary electrons produced at the aperatures. Similarly the channeltron only counted beam particles because of the bias on the second plate. Optimum biases were +30V on the first plate and +15V on the second.

The beam was attenuated as follows:

$$\text{Fraction Transmitted} = \frac{\text{Area Faraday Cup Aperature}}{\text{Area of Beam}}$$

$$= \frac{(10 \text{ x } 10^{-6}\text{m})^2}{(1.5875 \text{ x } 10^{-3}\text{m})^2}$$

$$= 3.97 \text{ x } 10^{-5} \text{ .}$$

The largest errors in determining the absolute efficiency resulted from the geometrical uncertainty. The aperature diameters were measured optically. The estimated error in the attenuation factor is less than five percent.

The vacuum system used was constructed of stainless steel with a glass bell jar. Viton or copper gaskets were used on all conflat flanges. The system was roughed out using sorption pumps and the vacuum was maintained at less than 10^{-7} torr by a 150 litre per second Ion Equipment diode pump. In this way loss of CEM gain due to oil contamination$^{(5)}$ was avoided.

Charged particle beams incident on the aperature system could be observed to check shape and size by observing the interaction with a fluorescent screen which could be rotated into the beam as desired.

3. CHANNELTRON CHARACTERISTICS FOR ELECTRON DETECTION

3.1 Procedure

Figure 2 shows the apparatus as set up for this part of the experiment. The electrons were generated by a hot filament and accelerated by 0 to 8 kV. The upper limit was determined by insulator breakdown. It is probable that 30 kV could be reached with only minor modifications to the ceramic insulator arrangement.

The beam as observed on the fluorescent screen was approximately 4 mm diameter. The screen was then removed and the channeltron count rate was maximized by applying an appropriate potential to the X-Y alignment plates.

To compensate for any small non-uniformities in the electron beam intensity, the beam was swept slightly in both directions by applying an AC signal to the plates. One set of plates was oscillated at 60 Hz, the other at 200 Hz.

The beam passed into the calibration chamber

(Fig. 1), the current was measured and the beam was attenuated before entering the channeltron. The channeltron pulses were processed with supporting electronics shown schematically in Figure 3. A 1024 Channel Nuclear Data Multi-channel Analyser was used for pulse height distributions. The current was sufficiently steady to be measured directly from the picoammeter with less than two percent error.

3.2 Discussion of Pulse Height Distribution and Gain

Although it is desirable in many applications to operate the channeltron in a pulse saturated mode, this was not possible in this experiment due to a maximum permissible operating voltage of 2500V. The Tennelec TC133 preamplifier could not exceed this voltage without breaking down. This is not a severe restriction as shown later. The pulse height distributions as a function of linear amplifier gain are shown qualitatively in Figure 4. A change in linear amplifier gain is expected to have a similar effect to a change in CEM gain resulting from altering the operating voltage. The gain was set at 100 for all experiments.

In a pulse saturated mode the gain is at a maximum possible level for a given level of fatigue.(6) For the Mullard channeltron used, the gain can be estimated roughly as follows:

Voltage of output pulse $\doteq$ 10V

Gain of linear amp. = 100

$\therefore$ pre-amp pulse height $\doteq$ 0.1V

Pre-amp is rated at 10^{12} V/Coul

$\therefore$ Charge output = $0.1\text{v} \times 10^{-12} \dfrac{\text{Coul}}{\text{V}}$ per incident electron and Gain = $10^{-13} \dfrac{\text{Coul}}{e^-} \times \dfrac{6.2 \times 10^{18} e}{\text{Coul}}$

$$\doteq 6 \times 10^5$$

The maximum gain for this type of CEM is given by Mullard as 1.3×10^8 (5) for operating voltages of up to 4kV. As mentioned, the lower gain associated with the lower operating voltage can be directly compensated for by raising the linear amplifier gain. In doing this the pulse height distributions are expected to be broader(7,8) and the signal to noise ratio slightly decreased. The actual number of output pulses detected should not decrease significantly, therefore the efficiency is virtually the same for the saturated or unsaturated operation.

The pulse height distribution shown in Figure 5 is somewhat broader than those published by Egide et.al.(6) as expected. The flux used for Figure 5 was 2×10^4 electrons/sec which was still below breakdown for the CEM used. The large number of pulses less than 0.2V is attributed to noise. By setting scaler thresholds at 0.2V the noise is ignored while less than one percent of the valid pulses are missed. Using less noisy electronics and lower thresholds can only increase the efficiency over values obtained in the paper by at most one percent.

3.3 Efficiency versus Input Flux

The channeltron efficiency is very sensitive to flux of incident electrons. Referring to Figure 6 it is apparent that the efficiency is constant over three orders of magnitude of input current while input rates of over 20,000 counts per second cause breakdown which gives misleadingly high efficiency.

Above roughly 50 c/s the efficiency is a constant while below this value the efficiency tends toward 100% which suggests that there may be two modes of operation in the CEM. Adams and Manley(8) suggested that the resistive coating of the channeltron has associated with it a recovery time after pulse transmission. Accordingly at very low count rates the pulses are separted sufficiently that all are counted but this hypothesis does not in itself adequately explain why the efficiency becomes a constant. A refinement to the theory is proposed in the following section.

It should be noted that the following is only a plausibility argument and is not as yet supported by experimental observation other than has been reported here. It is conceivable that the flux phenomena is produced by some unknown noise inherent in the detection system. How this is possible is unexplained since when the electron beam was blocked with the fluorescent screen, the observed count rate was less than one count per thirty seconds.

3.3.1 Possible Explanation of Channeltron Efficiency versus Flux

If it is assumed, as has been shown experimentally[(9,10)], that the frequency distribution of number of secondary electrons emitted per incident particle is Poissonian with mean γ, then the probability of no secondaries is

$$P(n=0) = \exp(-\gamma) \ .$$

The probability of at least one electron is then

$$P(n \geqslant 1) = 1 - \exp(-\gamma) \ ,$$

which is also the CEM efficiency assuming that the rest of the tube reacts to at least one of the secondaries produced in the first event.

Once an event has occurred in the cone, charge cannot instantly redistribute itself due to the very high resistance. This results in a localized perturbation of the electric field. It is reasonable to assume that in regions so affected the secondary emission coefficient will be different and presumably lower than for the non-disturbed areas. Certainly any of these disturbed areas will vary statistically in both the area and the duration of the perturbation but it is possible to substitute an average area and time in calculations.

As the input rate increases a larger fraction of the cone wall is in the low γ state at any given instant so the efficiency drops accordingly. The efficiency reaches a constant level when the entire cone is in the low γ state.

Mathematically, the model can be explained as follows:

N - input rate

A - total area of perturbation on cone surface

t - duration of perturbation

γ_1, γ_2 - secondary emission coefficients of mutiplying surface in un-perturbed and perturbed states, respectively.

Let total multiplying surface be one unit of area. The rate of change of perturbed area A is equal to the unaffected area (1 - A) times the change in Nt.

$$dA = (1 - A)d(Nt) .$$

Nt is a dimensionless parameter giving the number of damaged areas at any given time. The solution is

$$A = 1 - Ce^{-Nt} \quad , C = \text{constant.}$$

For N = 0, A must be zero so C = 1. The probability of getting at least one electron from an incident electron is

$P(e) = P(e^- \mid \text{incident hit unaltered area}) * P(\text{unaltered area})$

$\quad + P(e^- \mid \text{incident hit perturbed area}) * P(\text{perturbed area}).$

also

$$P(\text{unaffected area}) + P(\text{affected area}) = 1$$

so

$$P(e) = (1 - e^{-\gamma_1})e^{-Nt} + (1 - e^{-\gamma_2})(1 - e^{-Nt})$$

$$= 1 - e^{-Nt}(e^{-\gamma_1} - e^{-\gamma_2}) - e^{-\gamma_2} \quad ,$$

$$\lim_{N\to 0} P(e) = 1 - e^{-\gamma_1}$$

$$\lim_{N\to\infty} P(e) = 1 - e^{-\gamma_2}$$

The curves of Figures 6 and 7 indicate that γ_1 and γ_2 should be about 5 and 0.9, respectively for 4 kV electrons. Using these values and the model developed, Fig. 8 was produced on a computer. The results plotted seem to agree well with the experiment. Independent experiments must be designed to determine whether the observed behaviour is indeed a perturbation of the CEM wall, or simply induced by noise, or a manifestation of a parameter which has not been considered.

3.4 Other Factors Affecting Efficiency

Several factors influence the efficiency which is directly correlated to changes in γ_1 and γ_2. These factors include variations in

(a) energy of incident particle
(b) type of incident particle
(c) physical state of multiplying surface
(d) operating conditions of channeltron.

These efficiency variations are apparent in Figure 6. Egide et.al.(6) observed a decrease in channeltron gain with time which they termed fatigue. In these experiments a corresponding decrease in efficiency was observed, probably due to pulses becoming too small to be counted. For a 4 kV beam of electrons the efficiency dropped five percent over six hours when beam currents were greater than 1000 particles per second. The base level used is the "fresh mode" efficiency of the CEM which had been inoperative for 85 h.

An opposite effect was found for beam currents less than 400 c/s where efficiency greatly increased over a period of twelve hours (see Fig. 7). When the beam was shut off for six hours the efficiency dropped toward the fresh mode efficiency. This apparent contradiction is unexplained.

The conclusion is that if CEM counts are to have any qualitative value, readings must be made after several hours of operation under well controlled conditions, however if 10 to 15% errors in data can be tolerated, none of the aforementioned factors need be of concern.

3.5 Efficiency versus Energy

The CEM efficiency for electrons was found to have the energy dependence shown in Figure 9. The collected current was adjusted to 3×10^{-11}A or an input of 7×10^{3}c/s for each reading. Below 1 kV, stray magnetic fields caused some problems by bending the beam. μ-metal shielding minimized the effects but uncertainty in the data below 1 kV is arbitrarily set to ten percent.

4. LINEAR EFFICIENCY PARTICLE DETECTOR

The use of a channeltron to detect low energy atomic particles is complicated by the fact that different charge states are detected with different efficiencies. The detection efficiency for neutrals has not been accurately established because calibrated neutral beams are not available.

For these reasons a particle detector was proposed which would have the same response regardless of charge state and a linear response to energy following an idea first introduced by Morita(11). The basic principle is that the incident particle striking a metal foil produces secondary electrons which can be detected with nearly 100% efficiency by a channeltron.

4.1 Testing for Incident Electrons

To test the secondary detector, electrons were used to bombard gold foil and the secondaries were collected.

The calibration chamber used in the previous part of the experiment was replaced by the scattering chamber (Fig. 10). The electron beam produced as before hit a chemically etched gold foil at approximately 15° angle of incidence after being attenuated and measured by the same aperature system used before. The beam collection cup was left out of the chamber for this part of the experiment. The bias on the channeltron cone could be varied for either polarity while the operating voltage of the CEM was maintained at 2 kV. The supporting electronics is shown in Figure 11.

To verify that only secondary electrons were being collected the CEM cone bias was varied and the relative collection efficiency was recorded. The results plotted in Figure 12 show that for negative bias considerably fewer events were recorded implying that electrons were being repelled from the cone.

The effect of incident electron energy on the number of secondaries emitted is shown in Figure 13. The cone bias of the CEM was +300V so all secondaries collected had effectively the same energy. From the previous section the detection efficiency was close to unity. McDaniel(12) gives the maximum number of secondaries for clean gold foil as 1.45 per incident electron occurring at an energy of 800 eV. This is in excellent qualitative agreement with Figure 13 which maximizes at about 1 kV. The conclusion is that the channeltron collects only the secondary electrons from gold.

4.2 Testing with Protons

Knowing that the scattering detector discussed in the last section behaves as expected for incident electrons it was of interest to consider its characteristics using atomic primaries. For incident ions, it is expected that two types of secondary electron emission will occur.

(a) Potential emission at low energies

(b) Kinetic plus Potential emission at high energies

Based on these postulates we expect the number of secondary electrons per incident ion to be a constant below a certain cut-off and a linearly increasing function of incident ion energy above the cut-off. The kinetic portion will be linear up to about 20 kV which was out of the range of the accelerator used.

If incident neutral particles were used, the electron production by the metal foil should be the same as for ions minus the constant potential component.

4.2.1 Apparatus

The apparatus used to test the system for H^+ is shown in Figure 14. The protons were produced using an Ortec RF Ion Source to ionize H_2 gas. The ions were accelerated and magnetically energy analysed. A complimentary electrostatic analysis of the beam was not required since over 80% of the ion source output was protons (mv/q uniquely defines the energy in this case). The beam was passed through a 2 mm cold trap aperature to avoid contamination from the diffusion pump oil used for the accelerator.

The same scattering chamber was used as for electrons with the addition of an ion beam catcher. The beam catcher was a metal semi-cylinder mounted as in Figure 10. The reflected component of the incident beam passed through a grounded wire mesh into the 30V positively biased catcher. All secondary electrons generated by the reflected beam were therefore absorbed and did not reach the channeltron. The grounded screen ensured that there was no electric field acting on the gold foil. The grounded aperature in front of the CEM ensured that no stray electrons were attracted to the cone and counted. The chamber pressure as measured with an ion gauge was better than 10^{-6} torr while the bell jar pressure was 10^{-7} torr.

4.2.2 Results

To check that only secondary electrons were being collected, the cone bias was altered as before (Figure 12). It is clear that only electrons were being collected.

The quantity of interest is the relative number of secondaries collected per incident proton (v_c). In early experiments where the CEM was closer to the gold target, v_c was found to be fairly constant over the energy range scanned. This was because the solid angle was so large that the probability of collecting at least one of the secondaries was fairly high. When the CEM was moved further from the target v_c dropped considerably due to the smaller solid angle. More importantly the system was no longer saturated so it was possible to observe the effect of changes in energy on v_c. Figure 15 gives v_c in relative values as a function of proton energy. Considering uncertainties, the data does appear to lie on a straight line corresponding to kinetic plus potential emission. It was not possible to achieve low enough energies to see the kinetic component disappear. This is left for future work.

5. CONCLUSION

There does not seem to be any significant loss of data when the channeltron is operated below pulse saturation. The efficiency approaches 100% below 1 kV or when count rates drop below 100 counts/second. The channeltron is an extremely simple device both in construction and operation, but this simplicity implies that output data will be sensitive to environmental conditions. A small film of oxide or other contaminant may alter the CEM secondary emission coefficient considerably. A small change in γ can result in large changes in gain and efficiency.

The model developed for efficiency changes can easily be extended to account for changes in gain by considering changes in γ due to perturbations throughout the entire length of the CEM tube. The justification for the use of the model is still to be shown.

The linear response atomic particle detector appears to function as predicted but more tests are required especially in the low energy range. The detector will be useful in studies of backscatter particles from metals.

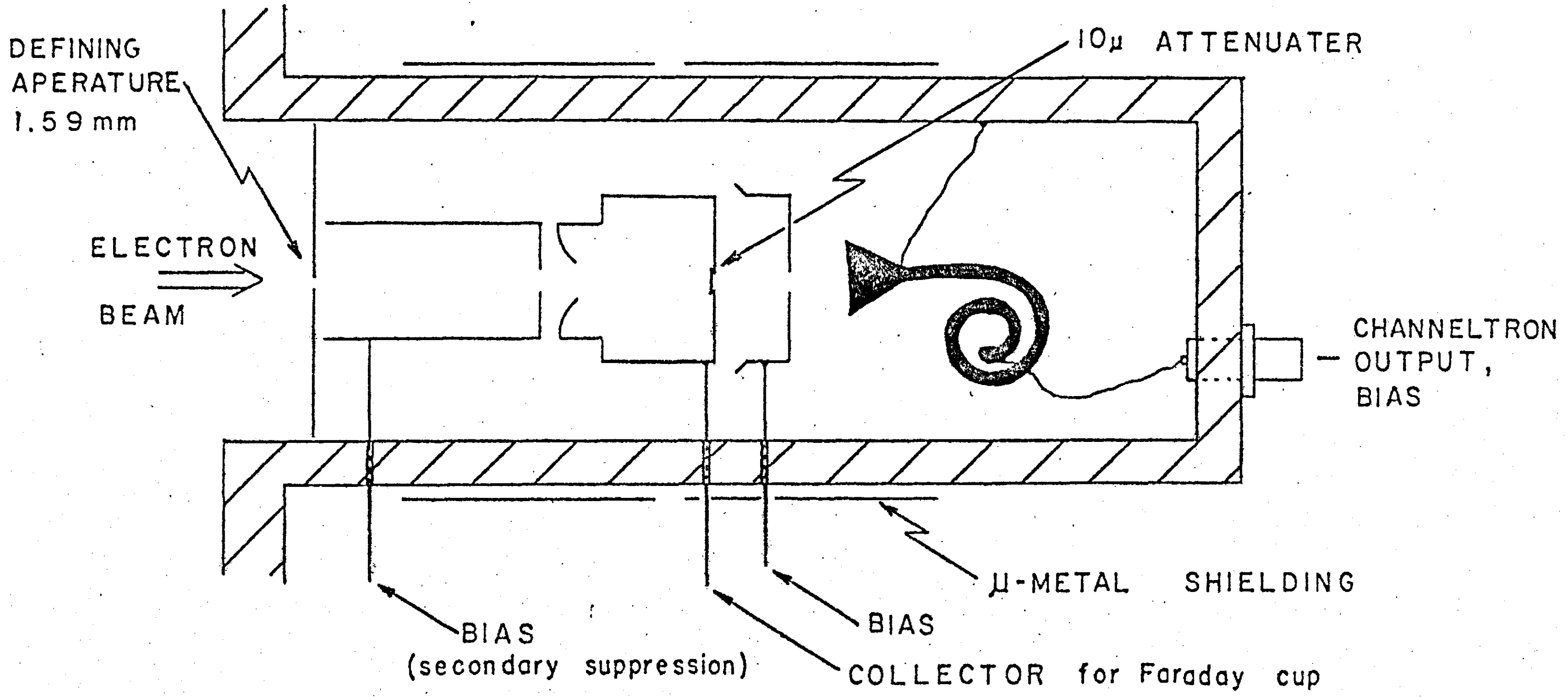

Figure 1. Electron beam calibration chamber.

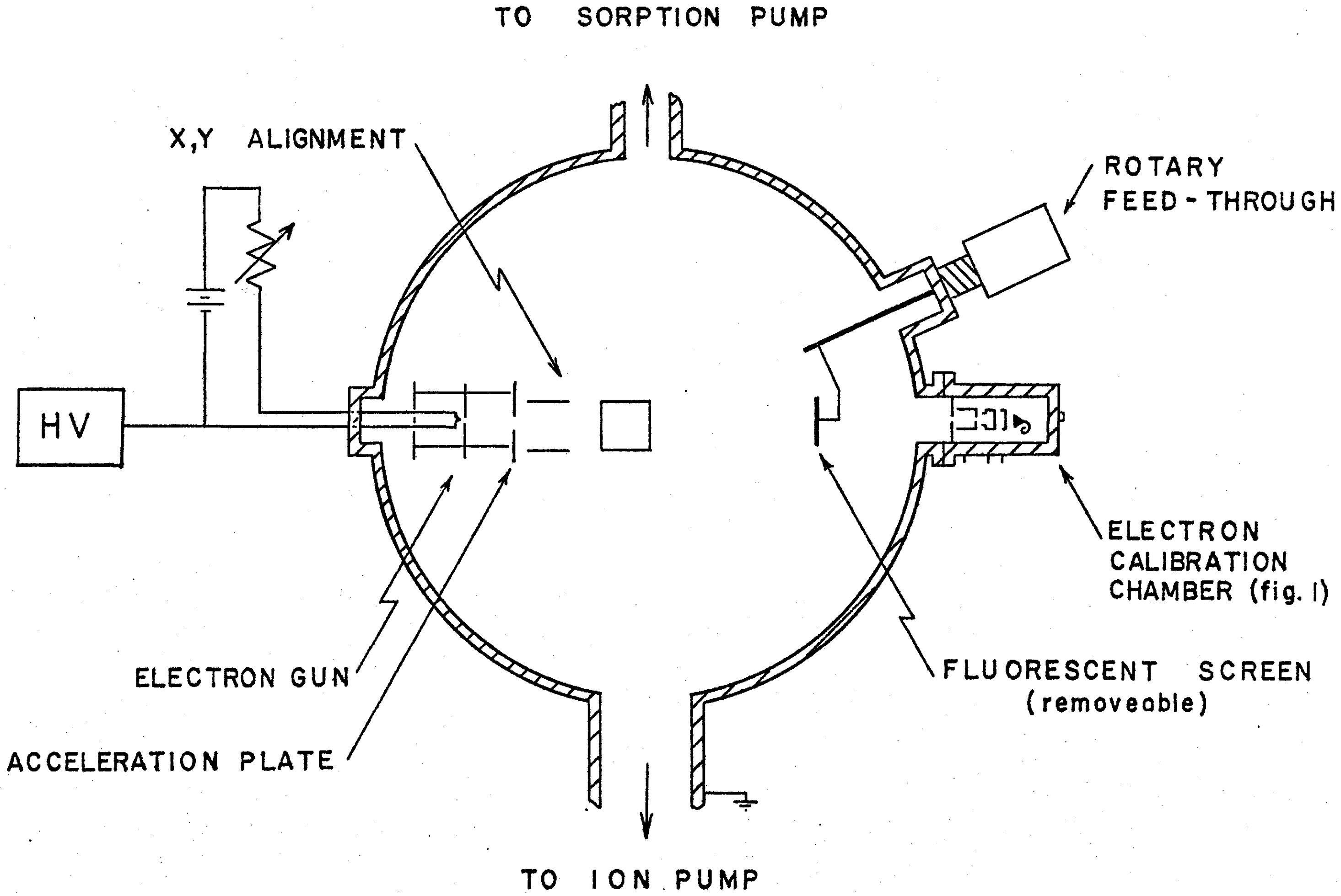

Figure 2. Apparatus for determining CEM electron characteristics.

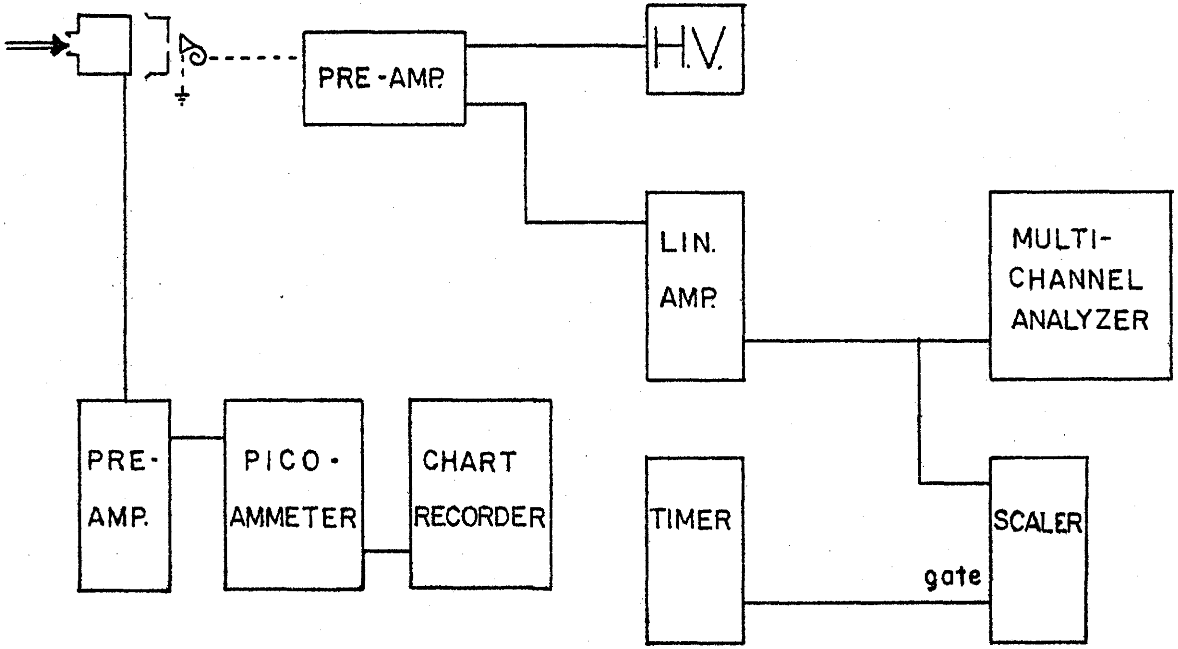

Figure 3. Electronics schematic for electron studies.

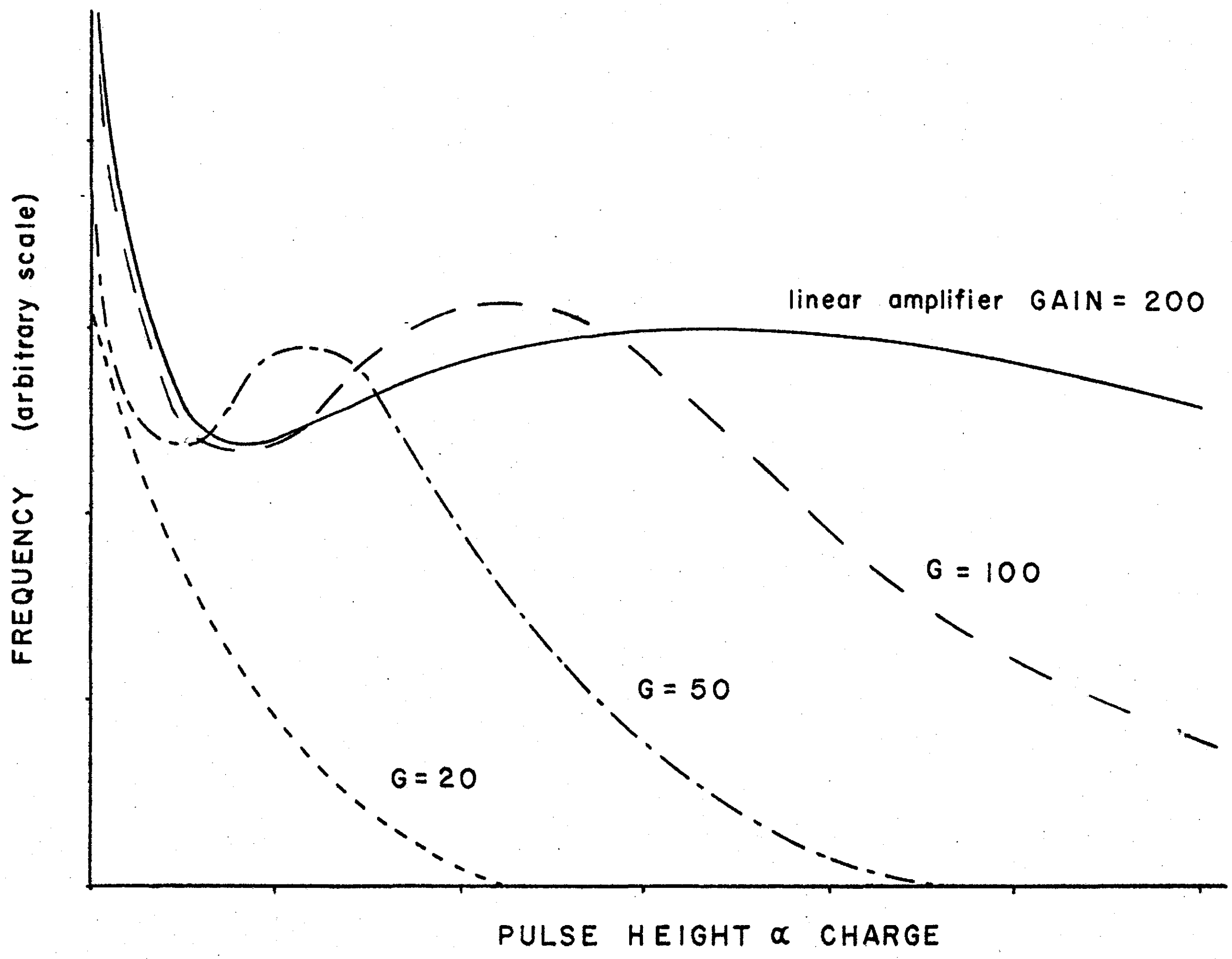

Figure 4. Pulse height distributions for different linear amplifier gains.

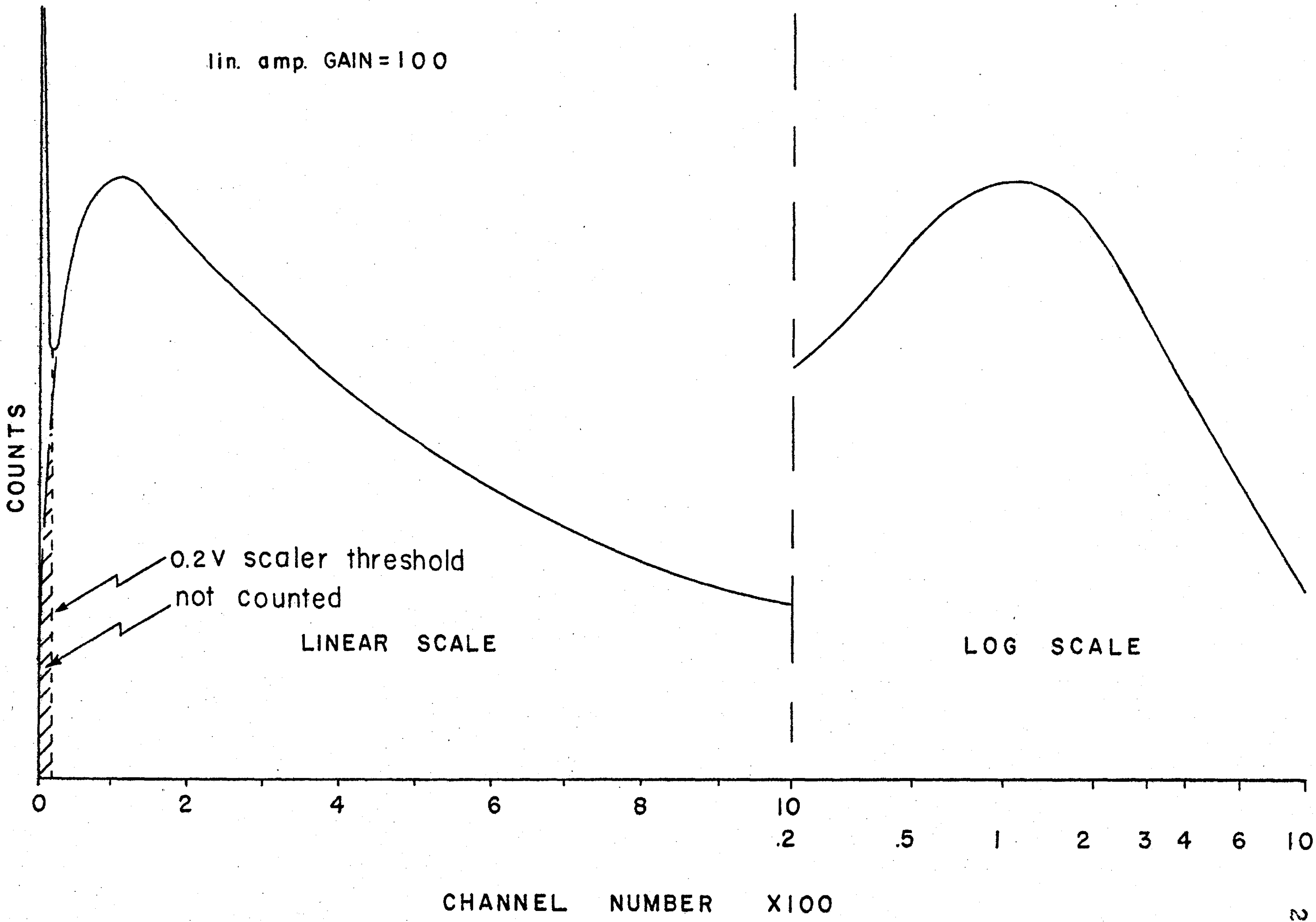

Figure 5. Pulse height distribution for linear amplifier gain of 100.

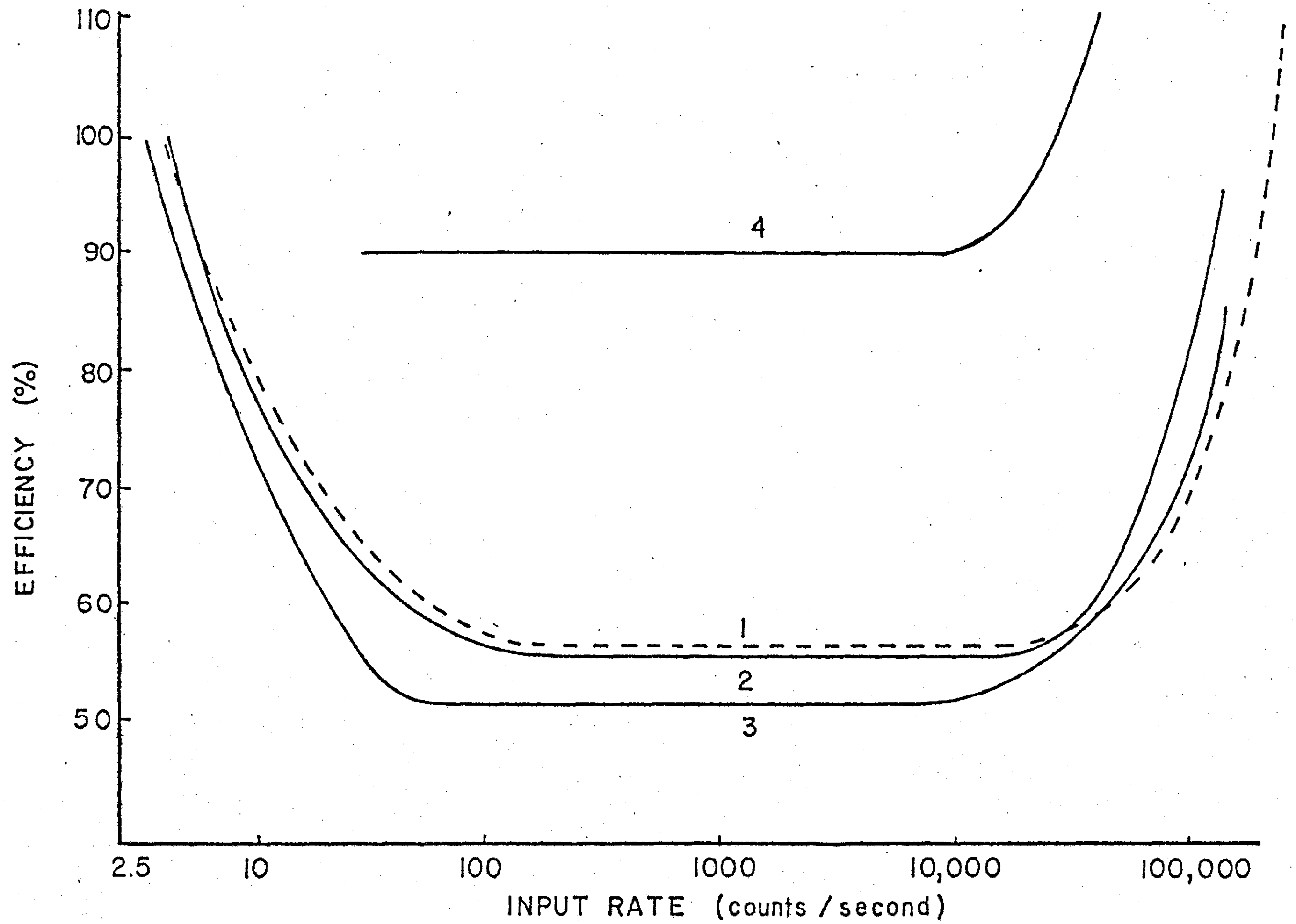

Figure 6. Efficiency vs. electron input rate.
1. "Fresh mode" CEM unused for over 85 h prior to test.
2. CEM input greater than 1000 c/s for 1.25 h. 4 kV electrons
3. CEM input larger than 1000 c/s for 6 h. 4 kV electrons
4. Typical efficiency response for 1 kV electrons.

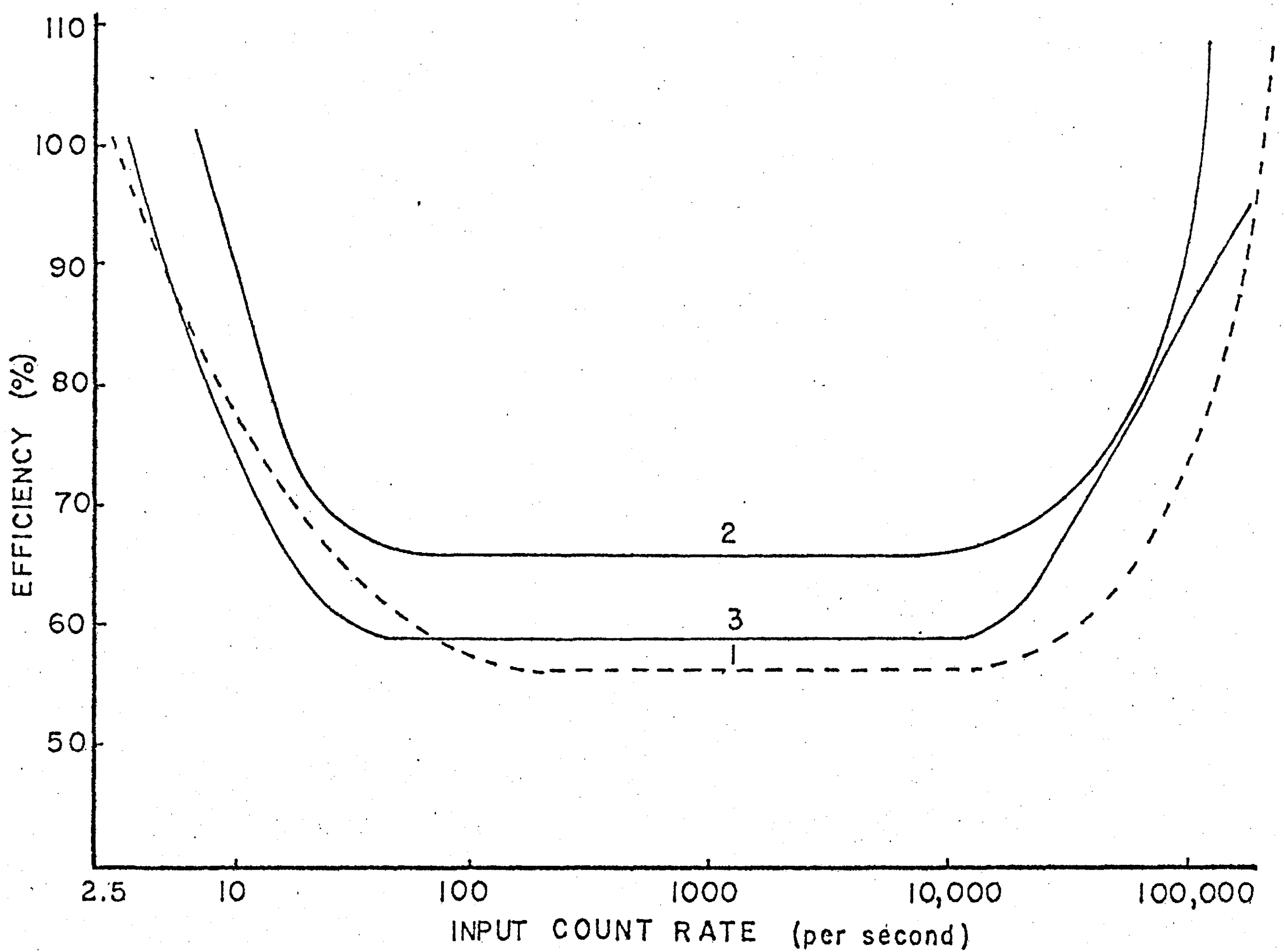

Figure 7. Efficiency vs. electron input rate.
1. "Fresh mode" CEM unused for over 85 h prior to test.
2. Input rate was 360 c/s for 12 h prior to experiment. An additional 4 h caused no change.
3. No beam for several hours. Efficiency drops toward (1)

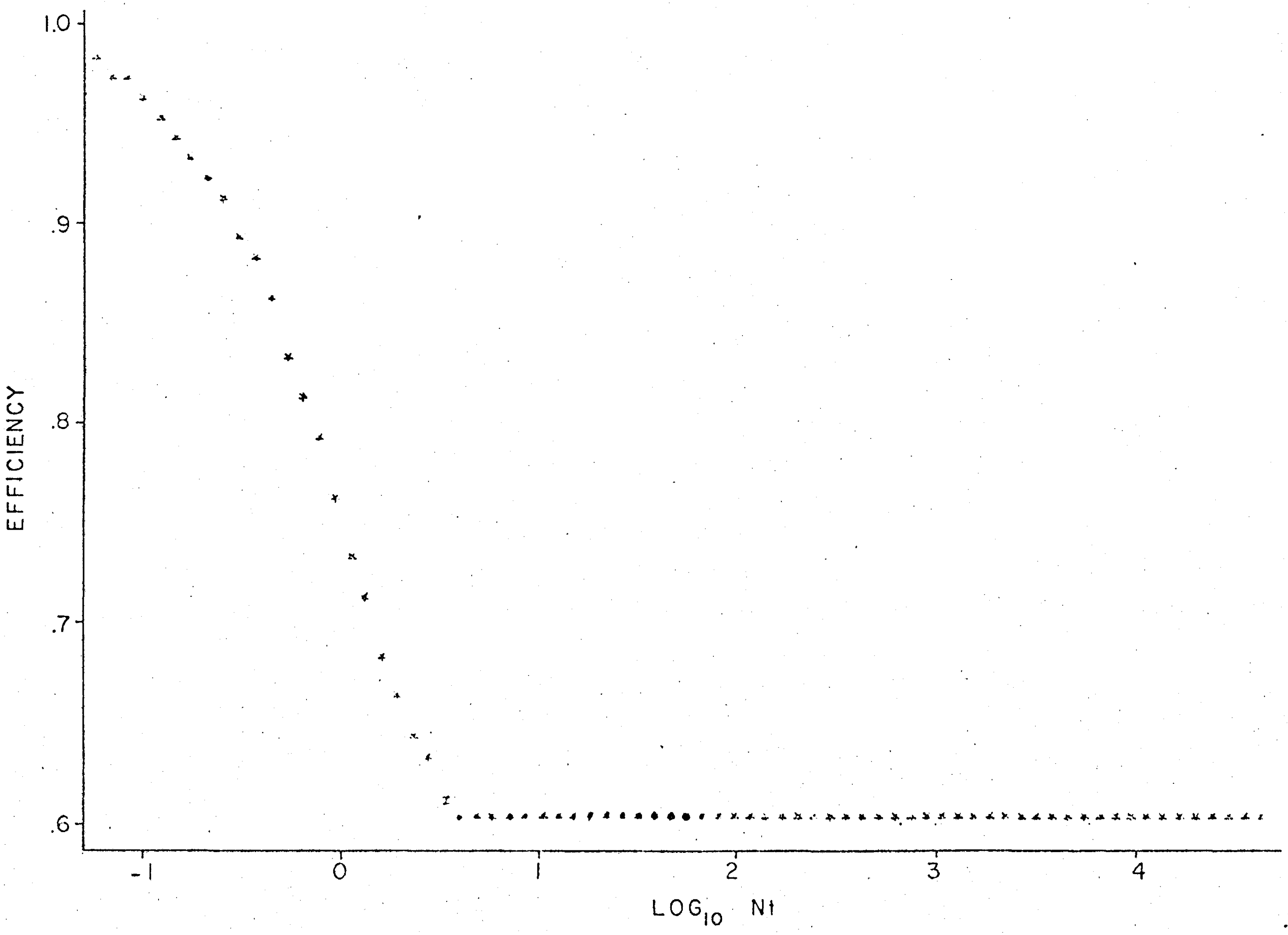

Figure 3. Computer generated efficiency curve to model typical behaviour for 4 keV electrons.

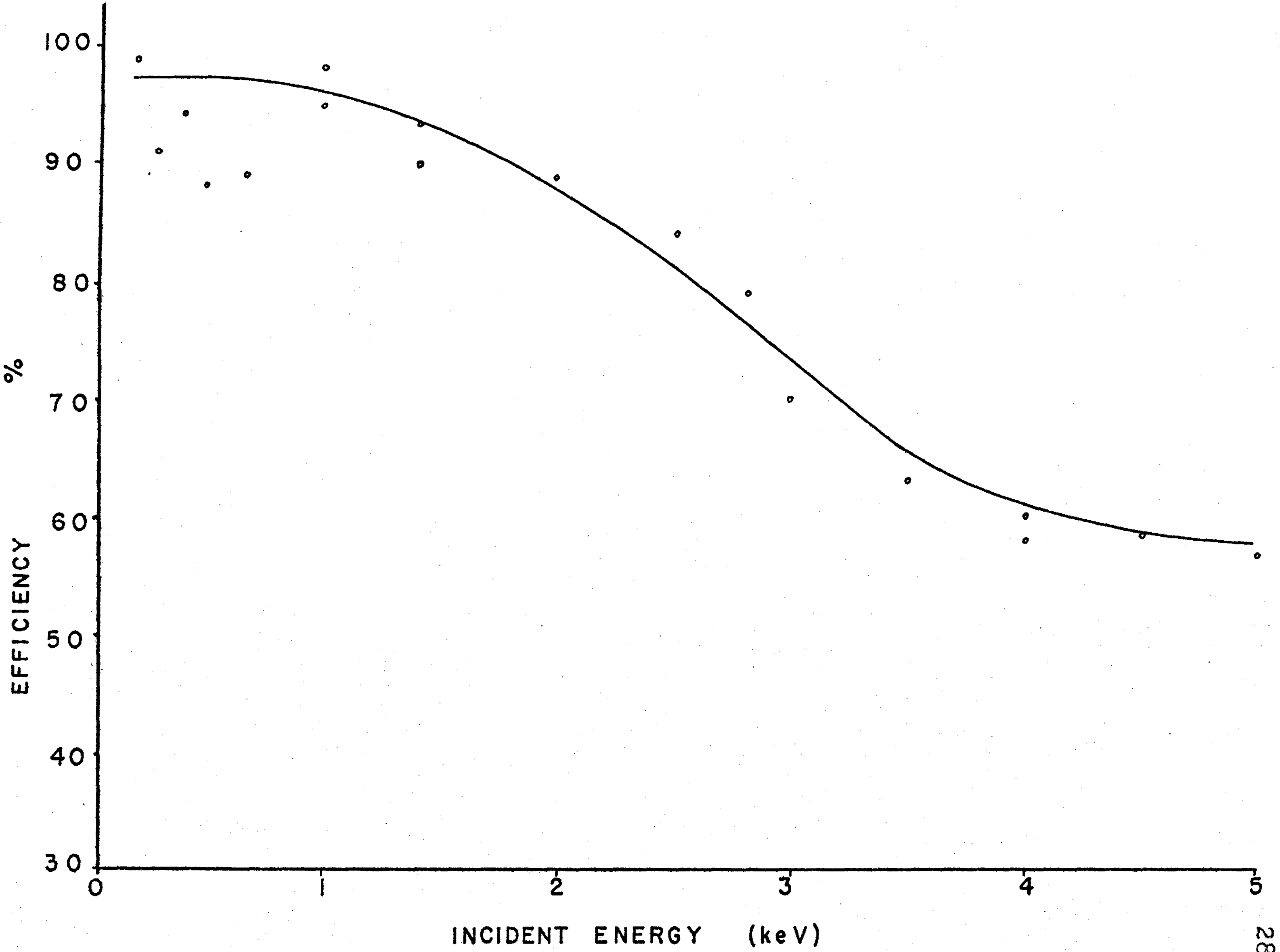

Figure 9. Efficiency vs. incident electron energy.

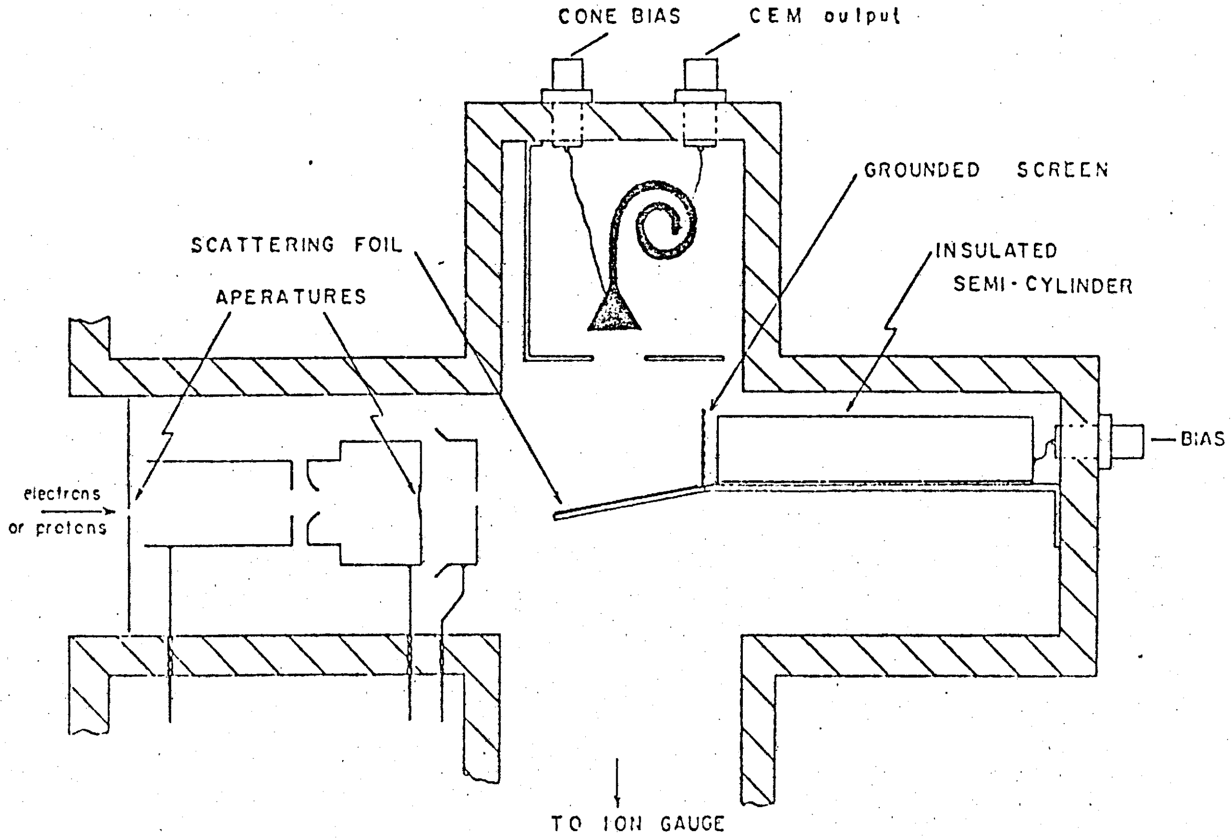

Figure 10. Scattering chamber.
(semi-cylinder was not used for electron test)

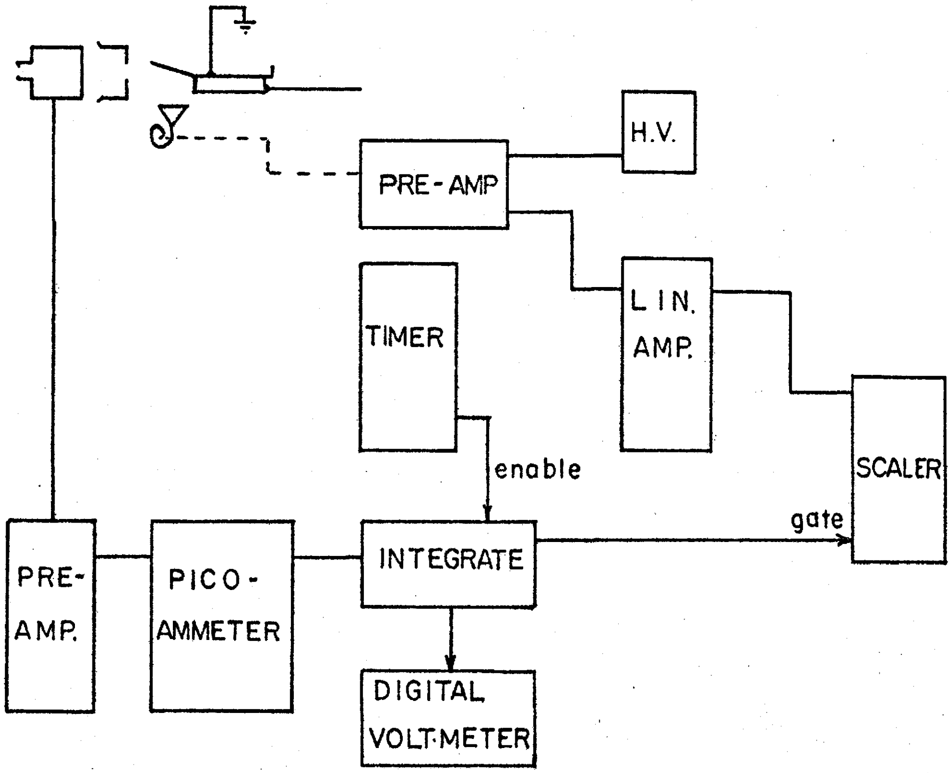

Figure 11. Scattering studies electronics schematic.

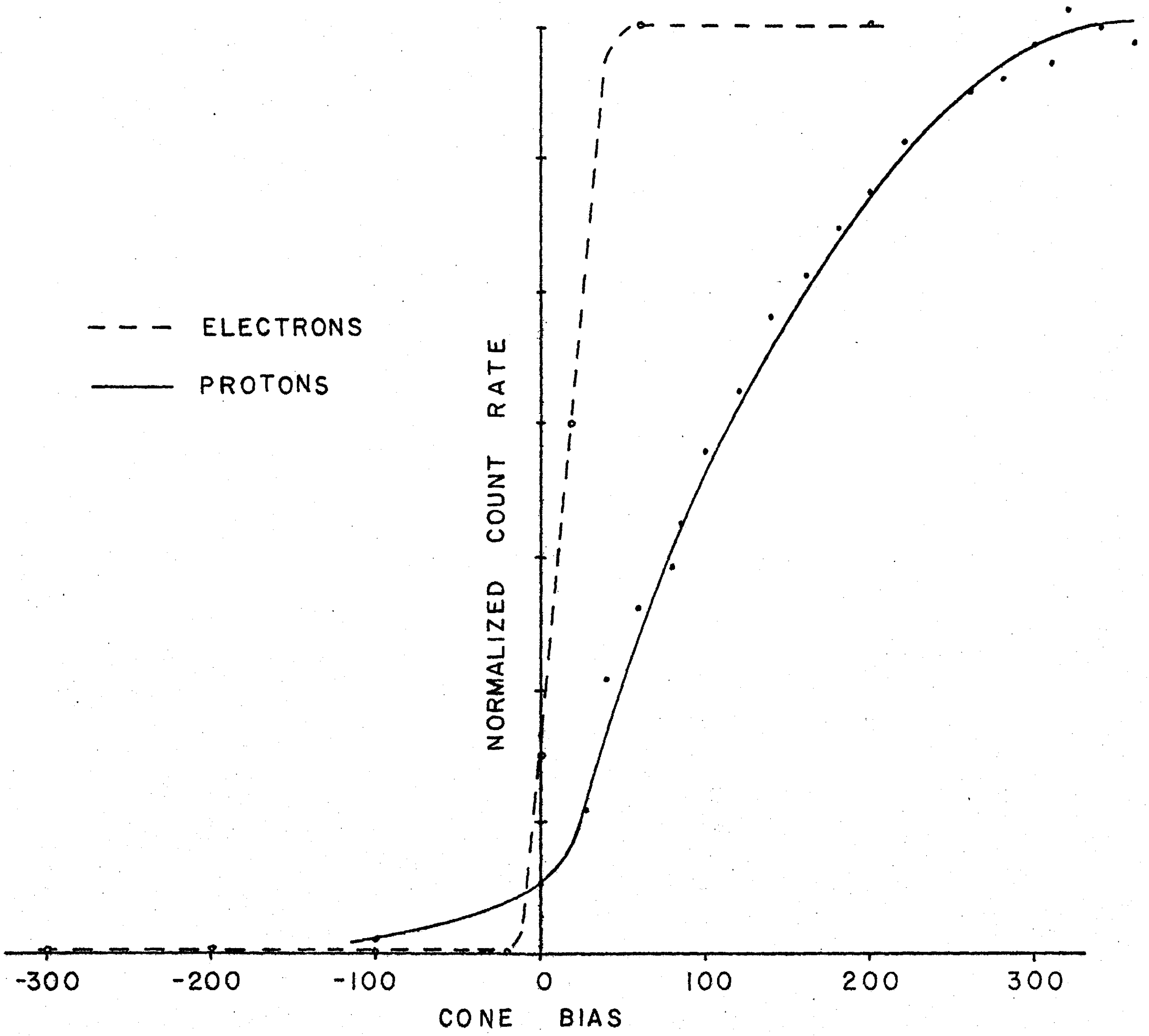

Figure 12. Count rate vs. CEM cone bias: Foil-channeltron detector.

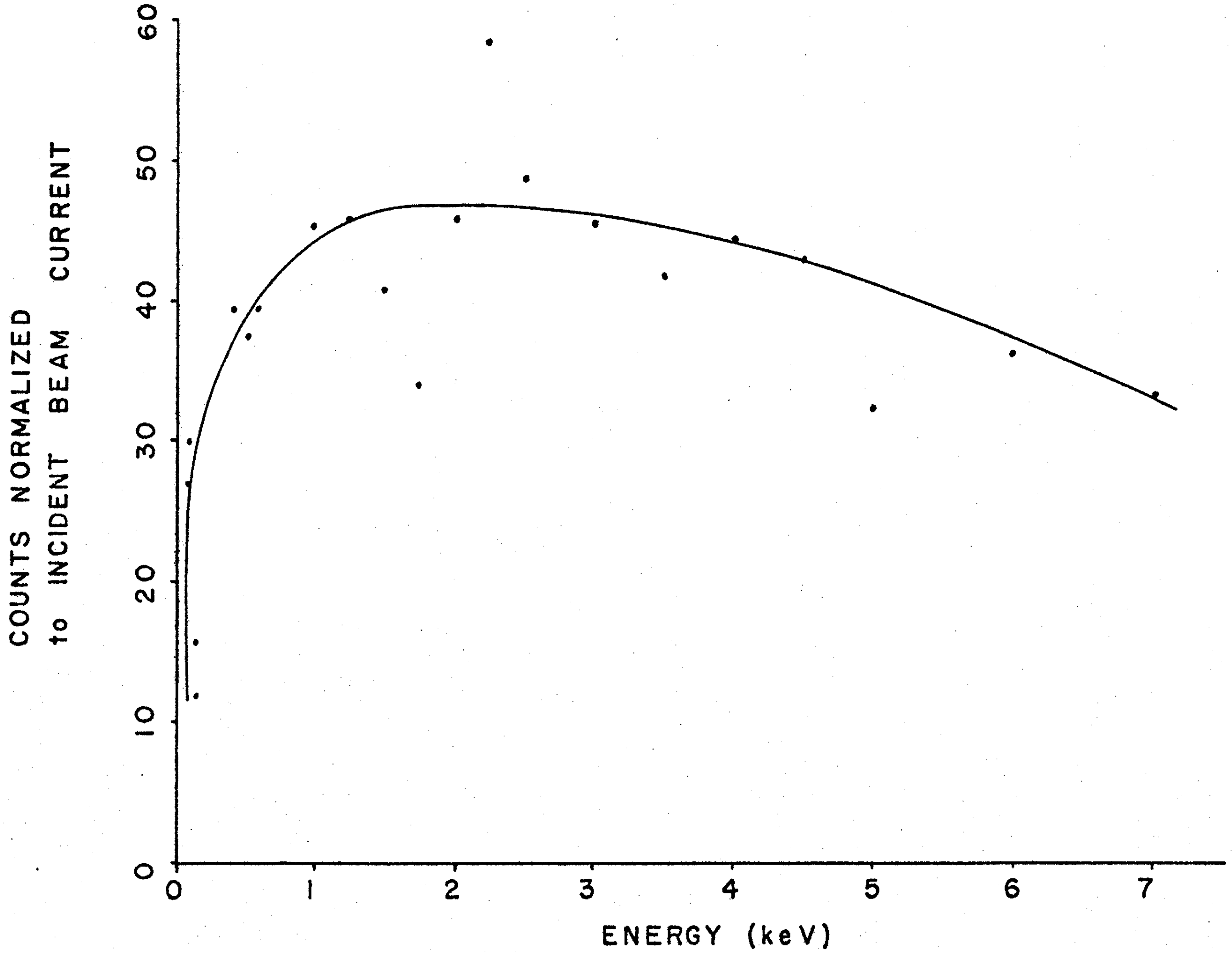

Figure 13. Count rate vs. energy to verify that the electrons collected were secondaries from gold.

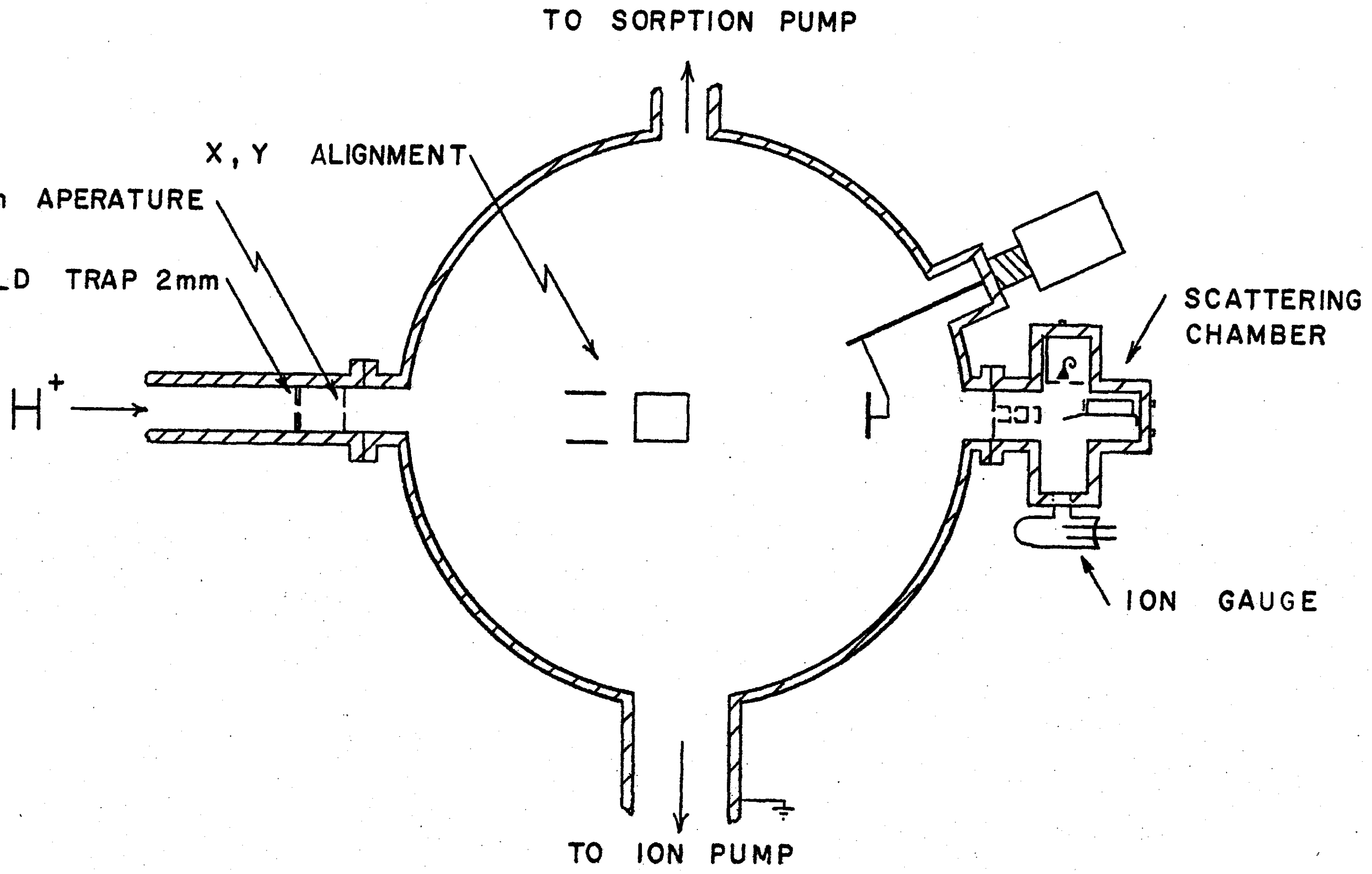

Figure 14. Apparatus for proton scattering equipment.

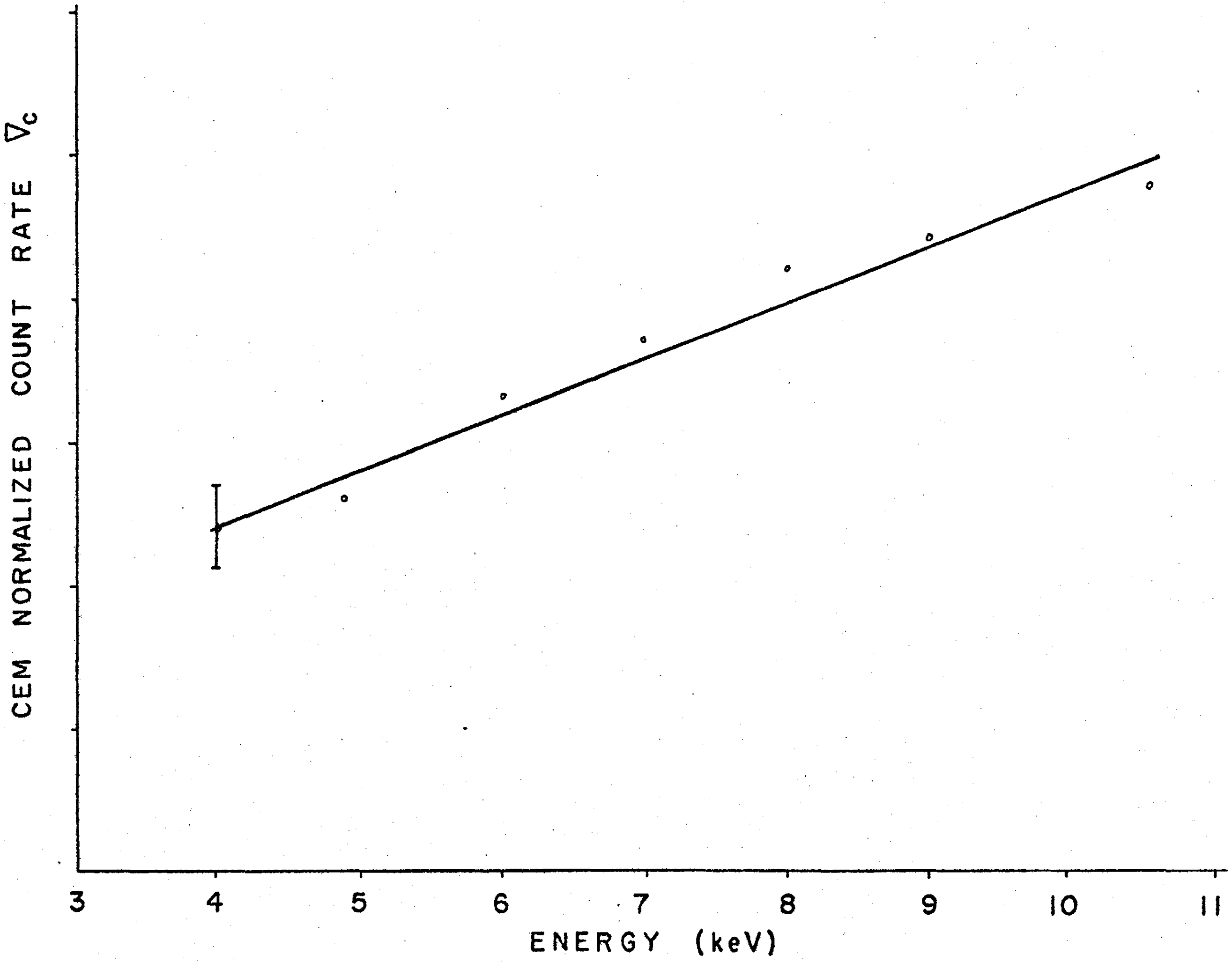

Figure 15. Foil-channeltron detector count rate vs. proton energy.

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