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RESPONSE OF LOW DENSITY KCl FOILS TO MULTI-MeV ELECTRONS*

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As part of a detector development program being carried out at SLAC, the secondary yield (gain) of low density KCl dynodes has been measured over the range of primary energies from 100 to 1000 MeV. The dynodes were prepared by evaporating KCl at a few Torr of argon, and the gain for 10 keV primaries was determined to be 50-60 secondaries per primary. The secondary yield for minimum ionizing primaries was found to be 5-6, to increase logarithmically with increasing primary energy, and to decrease rapidly with increasing beam intensity above an average current of $\sim 5 \times 10^{-8}$ A/cm^2. The results are in good agreement with present theories on the relativistic rise in the ionization loss of high energy particles and with earlier experimental results on the energy dependence of the efficiency of metal foil secondary emission beam monitors.

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I. Introduction

The high gain and fast response time reported by Goetze, et al.[1,2] for low density KCl dynodes make their application to direct particle detection as envisioned by Alvarez and Cone[3] seem promising. At multi-GeV primary energies, determination of the rest mass of a "counted" particle becomes very difficult because of the multiplicity of possible final states of an interaction. If the secondary yield of low density foils is $\gtrsim 5$ for minimum ionizing particles, follows the relativistic rise in the ionization loss, and has a reasonable statistical number distribution, then velocity determination (and, hence, rest mass determination if the momentum is known) of primary radiation is readily achievable with an array of foils. A single such foil, coupled to a multiplier section, would act not only as a particle detector but could give excellent space and time resolution.

The present work was undertaken to investigate the possibility of using low density deposits in a relativistic rise detector. It was found that 5-6 secondaries per primary are obtained, on the average, from low density KCl for primary electrons of energy from 100 to 1000 MeV, and that the gain follows closely the relativistic rise in the ionization loss.

II. Dynode Preparation

A cross-section of a low density dynode is shown in Fig. 1. The substrate consists of a 1-inch diameter, 1000 Å thick self-supporting Al_2O_3 film formed by an anodization-etching technique similar to that of Hauser and Kerler.[4] A 500 Å thick Al conductive backing is deposited by thermal evaporation on the Al_2O_3. Low density KCl is deposited on a room temperature substrate by evaporation from a Ta boat at a pressure of a few Torr of argon.[2] Typically, 25 mg of KCl is evaporated at 4 Torr static argon pressure, using a 2-inch boat-to-substrate spacing; the KCl is first melted and then is evaporated in $\sim$ 20 sec. This gives a dynode with a thickness of $\simeq 25\mu$ and a density of 2-3% of the bulk density. Low density CsI is prepared in essentially the same way except a Mo boat is used and the evaporation time is longer ($\simeq$ 100 sec); CsI dynodes are $\simeq 30\mu$ thick and have $\simeq$ 2% of the bulk density. Density and thickness of the dynodes was determined by weighing and measuring thickness with an optical microscope in a separate calibration using a standard evaporation procedure.

All evaporations were performed in a diffusion-pumped, freon-refrigerator-baffled, unbaked vacuum system with a base pressure $\sim 2 \times 10^{-7}$ Torr. Dynodes were transferred to small ion-pumped, all-metal, vacuum systems (base pressure $\sim 5 \times 10^{-9}$ Torr) for measurement of the gain; transferring of the dynodes was carried out in an atmosphere of dry nitrogen. The gain at low primary energies, $\sim$ 10 keV, was measured (see Fig. 1) using a Au photocathode illuminated by a BH-6 high pressure Hg lamp.[5] Typical gain (δ) vs collector potential (V_c) characteristics are shown in Fig. 2. These results for low density KCl are in good agreement with the data reported by

Goetze, et al.[2] The low energy characteristics were found to be unaffected by bombardment with multi-MeV electrons.

III. Measurement Technique

Gain measurements for multi-MeV primary electrons were carried out at the Stanford Mark III linear electron accelerator. A photograph of the experimental arrangement is shown in Fig. 3. A Faraday cup was used to measure the primary current and was designed to be $> 99\%$ efficient over the range of primary energies investigated (100 - 1000 MeV).[6] The value of δ was determined from the slope of the curve (as plotted on an X-Y recorder) of integrated current leaving the dynode vs integrated current collected by the Faraday cup. Integrated current was measured, instead of the current itself, because of the large amount of electrical noise associated with the accelerator, as well as to remove effects of small beam current fluctuations. A collector potential of 165 V was used in the present experiment because at higher potentials the gain of KCl was not sufficiently stable. Sporadic increases in δ manifested themselves as steps in the curves. These steps occurred very infrequently at $V_c = 165$ V and probably correspond to the scintillations reported by Goetze, et al.[2]

The measured values of δ presented here are averages of 5 or 6 separate determinations at a fixed value of primary energy (E_p), while the errors shown correspond to the range of values obtained. The beam was left on during the measurements at a fixed E_p to minimize discharging of the exit surface, but had to be turned off to change energy. After changing energy, the exit surface was given sufficient time to charge before the measurements were continued. The data was taken by monotonically decreasing the energy from maximum, and possible deterioration of δ under bombardment was checked by repeating the measurement at maximum energy. The energy of the primary beam was known to an accuracy of about $\pm$ 5 MeV.

IV. Results and Discussion

The gain of low density KCl dynodes was found to be strongly dependent on beam intensity as shown in Fig. 4 (average beam current in amperes $\simeq 10^{-17}$ x electrons per pulse). This effect is believed to be due to bombardment induced conductivity limiting the internal field. The few percent difference in δ for V_c = 165 and 200 V (apparent in Fig. 4) is consistent with the low energy data in Fig. 2. To minimize changes in δ resulting from changes in beam intensity, the energy dependence of δ was determined at a beam intensity of $(1.5 \pm 0.2) \times 10^8$ e^-/pulse. The results of these measurements are presented in Fig. 5. The logarithmic increase in δ with increasing energy is evident and arises from the relativistic rise in the ionization loss. The experimental points at the lowest primary energies may have been shifted by a few percent to higher values of δ by multiple scattering in the sapphire windows, which may cause electrons to miss the Faraday cup. It is obvious that the "downstream" data (i.e., with the primary beam incident on the Al_2O_3 side of the dynode, see Fig. 1) is lower, and the relativistic rise is slightly suppressed relative to the "upstream" data. This is in agreement with the theoretical considerations of Aggson on the density effect.[7] The density effect should become important when the field forming distance, l_p , is of the order of the film thickness, τ , that is, when:

$$l_p = \gamma \sqrt{\frac{2mc^2}{4\pi ne^2}} \simeq \tau \qquad (1)$$

where $\gamma = (1-\beta^2)^{-\frac{1}{2}} = (1-v^2/c^2)^{-\frac{1}{2}}$, m and e are the rest mass and charge of the electron, n is the atomic electron density of the material, and c is the velocity of light. For KCl, $l_p \simeq 45\mu$ at $E_p = 500$ MeV which is comparable with $\tau \simeq 25\mu$.

As shown in Fig. 6, this data is in good agreement with the slope of the experimental results of Richter[8] and the theoretical work of Aggson[7] on Al foil secondary emission monitors (SEM), but in only fair agreement with the theoretical work of Vanhuyse and Van De Vijer.[9] Curve 3 of Fig. 6 (with arbitrary normalization) was taken from the work of Vanhuyse and Van De Vijer and was calculated by them for an Al foil SEM. This calculation involved the theory of secondary emission from metals of Baroody;[10] the agreement with the present work on insulators reflects the insensitivity of the slope of the ionization loss formula to material parameters (which appear inside logarithms). Curve 2 of Fig. 6 was calculated using the Bethe-Bloch formula without density effect for collisions involving energy transfers less than a predetermined value, η :

$$\delta \propto - \frac{dE}{dx} = \frac{2\pi ne^4}{m\beta^2c^2} \left[\ln \frac{2m\beta^2c^2\eta}{I^2(1-\beta^2)} - \beta^2 \right] \qquad (2)$$

where η is the maximum energy transfer and I is the mean ionization potential. According to Aggson,[7] η is given by the solution of:

$$R(\eta) = \frac{d_s}{\cos\theta} = d_s \sqrt{\frac{2mc^2}{\eta}} \qquad (3)$$

where $R(\eta)$ is the range-energy relation for keV electrons, d_s the maximum depth from which secondaries can escape, and $\cos\theta$ the angle between the secondary and primary electron trajectories given by relativistic kinematics. Using the range-energy relation from the work of Kanter,[11] and the recently measured[12] value, $d_s = 7\ \mu g/cm^2$, Eq. (3) yields: $\eta = 4.6$ keV. The value $I = 10$ eV has been used in evaluating Eq. (2), curve 2 in Fig. 6. This calculation, normalized to $\delta = 5.1$ at 100 MeV, is in excellent agreement with the present experimental results.

The ability of two differing theories to give reasonable fits to the present data is merely a result of the logarithmic dependence of dE/dx on material parameters. However, the value of I used in the above calculation does not agree with the value calculated from the low energy data. Using the results reported by Kanter[11], it is estimated that $I \simeq 2$ eV/secondary. This apparent low value of I may be due to internal multiplication in the field enhanced emission process.[13]

Use of the tabulated[14] collision loss of a 500 MeV primary, the value of d_s given above, and $I = 2$ eV, allows calculation of $\delta(500\ \text{MeV}) = 5.95$ which is very close to the measured value of 5.67. Because I appears only within the logarithm in the Bethe-Bloch formula, the calculation of $\delta(500\ \text{MeV})$ is nearly independent of whether $I = 2$ eV with no internal multiplication, or $I = 10$ eV with internal multiplication by a factor of 5.

Very limited results on low density CsI dynodes were obtained for multi-MeV primary electrons. It was observed that δ for CsI dynodes was as much as 40 percent higher than for low density KCl dynodes.

V. Conclusions

The statistics of a single-particle detection device are determined almost entirely by the initial number of secondaries produced by the primary and a yield of at least 5 is required for accurate counting purposes. The data presented above indicate that an ensemble of low density KCl foils can be used for velocity determination and detection of relativistic particles unless the statistics of the secondary emission process are pathological such as to give, for example, 50 secondaries for 10% of the incident particles and 1 secondary for the rest, instead of 6 secondaries per primary, Poisson distributed. The question of internal multiplication is of crucial importance to the future applications of these dynodes to direct particle detection, and an experiment is planned at SLAC to determine the statistics of the field enhanced secondary emission process with relativistic primaries.

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Figure Captions:

Fig. 1 Cross-section of a low density dynode and the experimental arrangement for measuring the secondary yield.

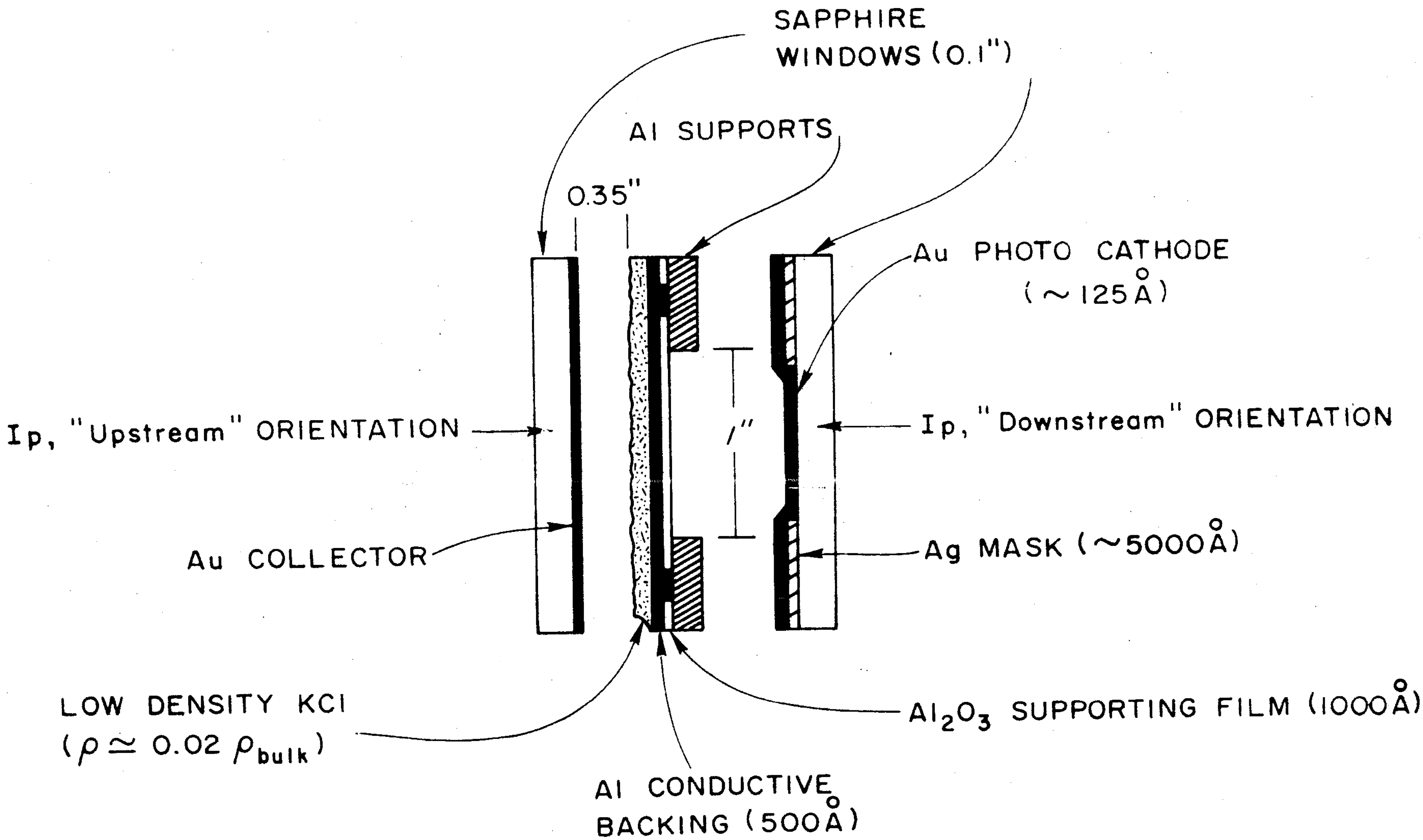
Fig. 2 Dynode gain vs collector potential for the low density dynodes used.

Fig. 3 Photograph of the experimental arrangement for measuring the secondary yield of low density dynodes at multi-MeV primary energies. (1) Vacuum system containing dynode, (2) Faraday cup, (3) End of the linear accelerator, (4) and (5) Television cameras for observing the beam spot on ZnS screens.

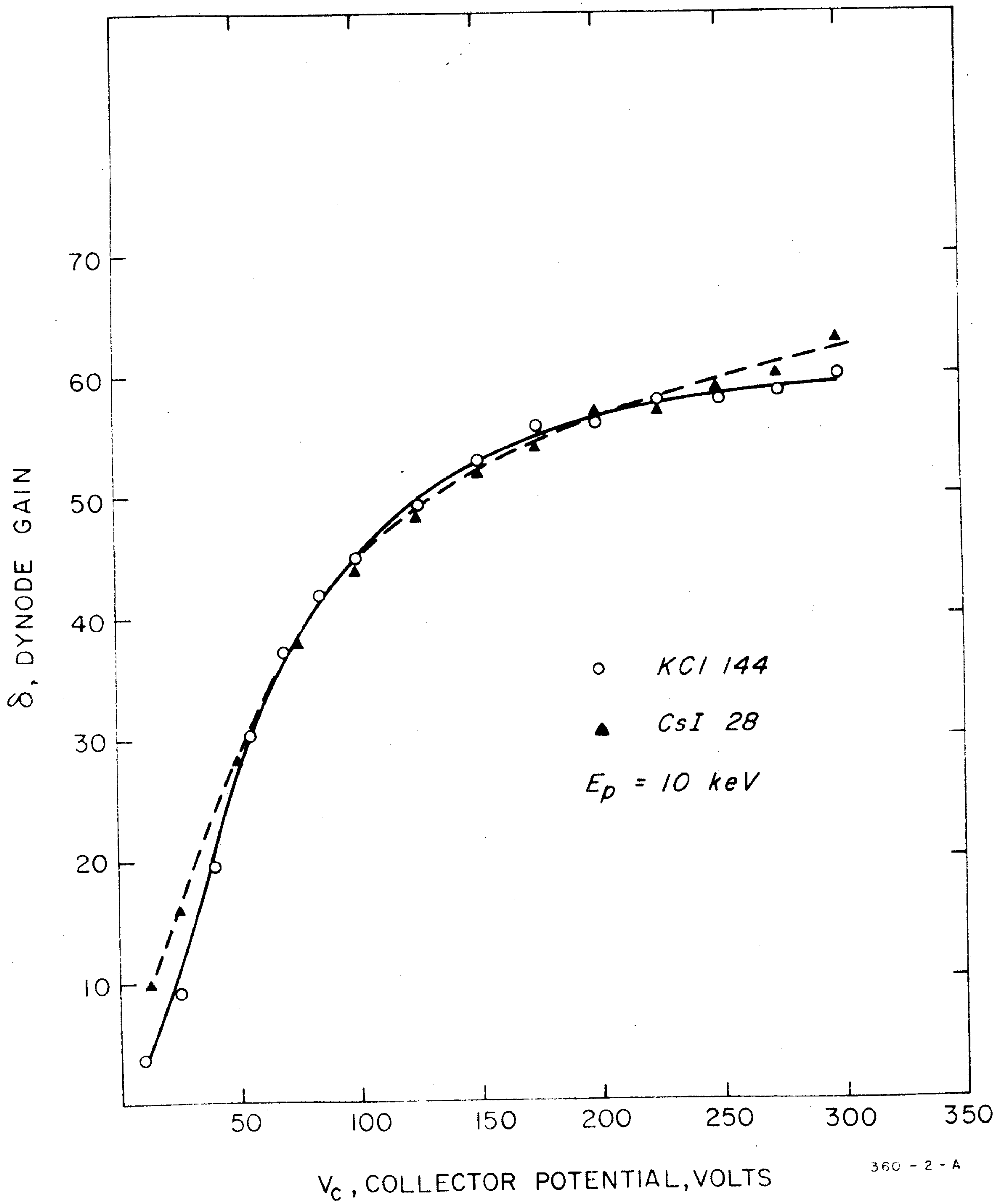
Fig. 4 Intensity dependence of the gain for a low density KCl dynode.

Fig. 5 Dynode gain vs primary energy for a low density KCl dynode.

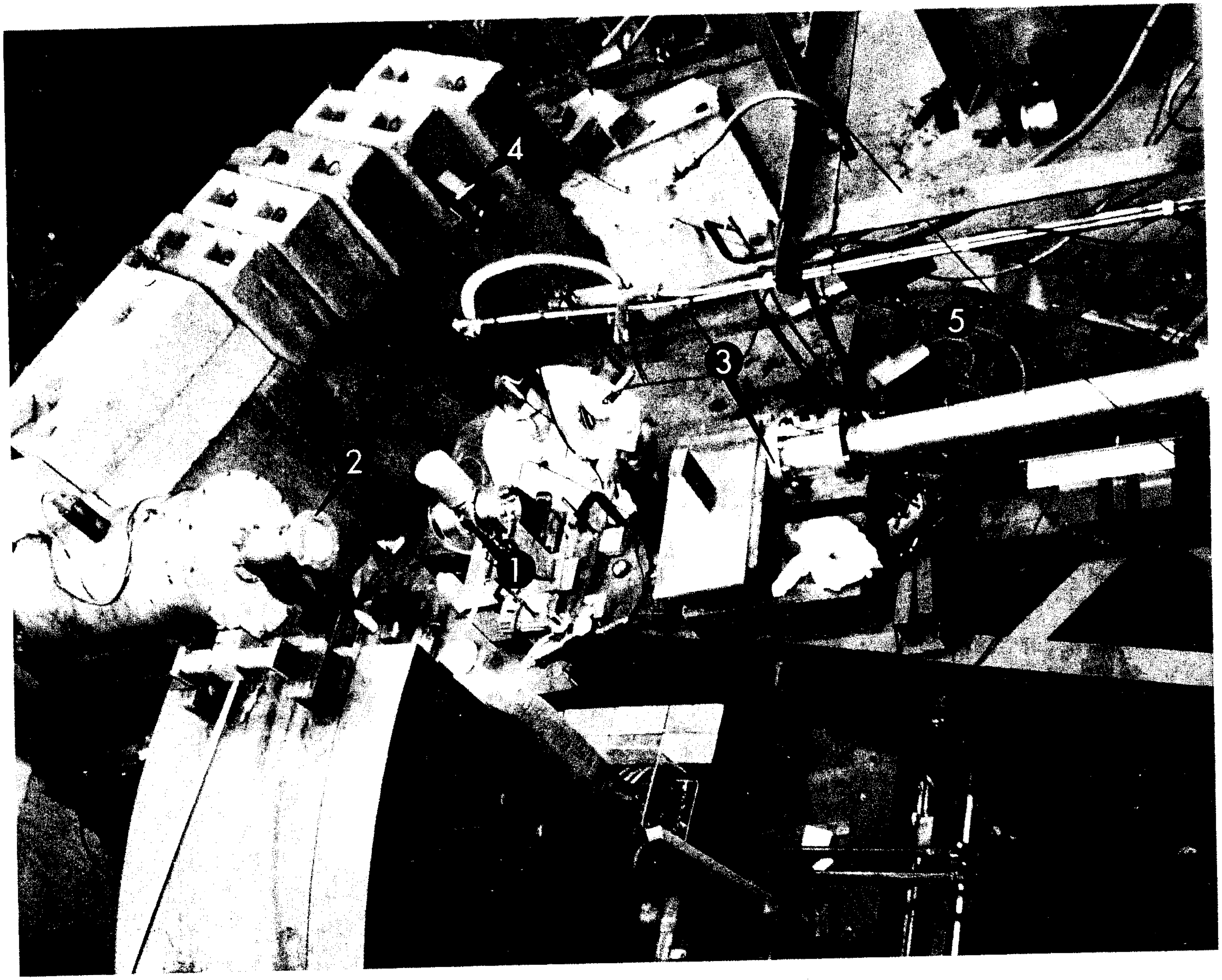
Fig. 6 A comparison of present data with other experimental and theoretical work.


SAPPHIRE
WINDOWS (0.1")
Al SUPPORTS
0.35"
Au PHOTO CATHODE
(~ 125 Å)
Ip, "Upstream" ORIENTATION
1"
Ip, "Downstream" ORIENTATION
Au COLLECTOR
Ag MASK (~5000 Å)
LOW DENSITY KCl
($\rho \simeq 0.02\ \rho_{bulk}$)
Al_2O_3 SUPPORTING FILM (1000 Å)
Al CONDUCTIVE
BACKING (500 Å)

360-1-A



δ, DYNODE GAIN
70
60
50
40
30
20
10
50
100
150
200
250
300
350
KCl 144
CsI 28
E_p = 10 keV
V_c, COLLECTOR POTENTIAL, VOLTS
360 - 2 - A


4
5
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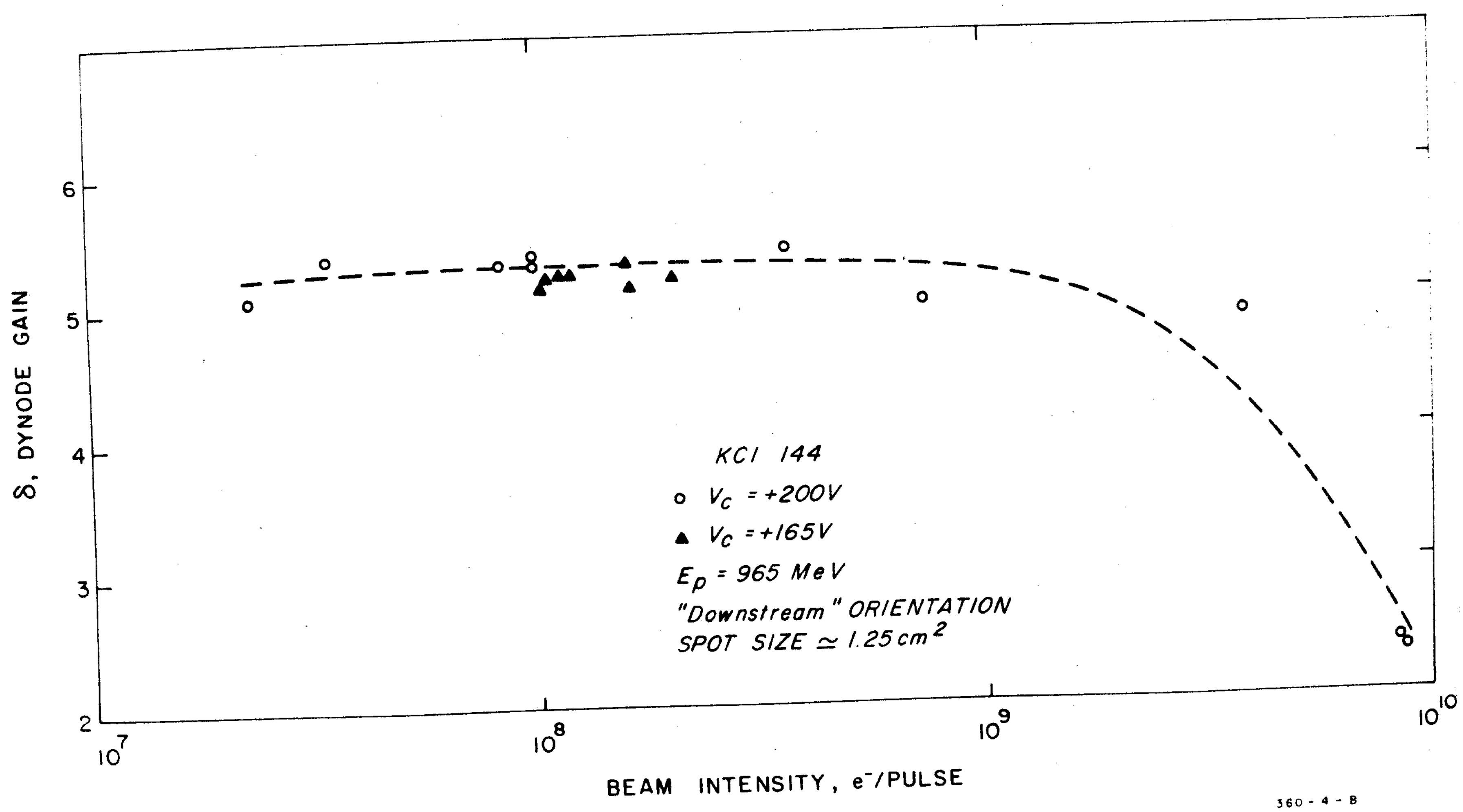
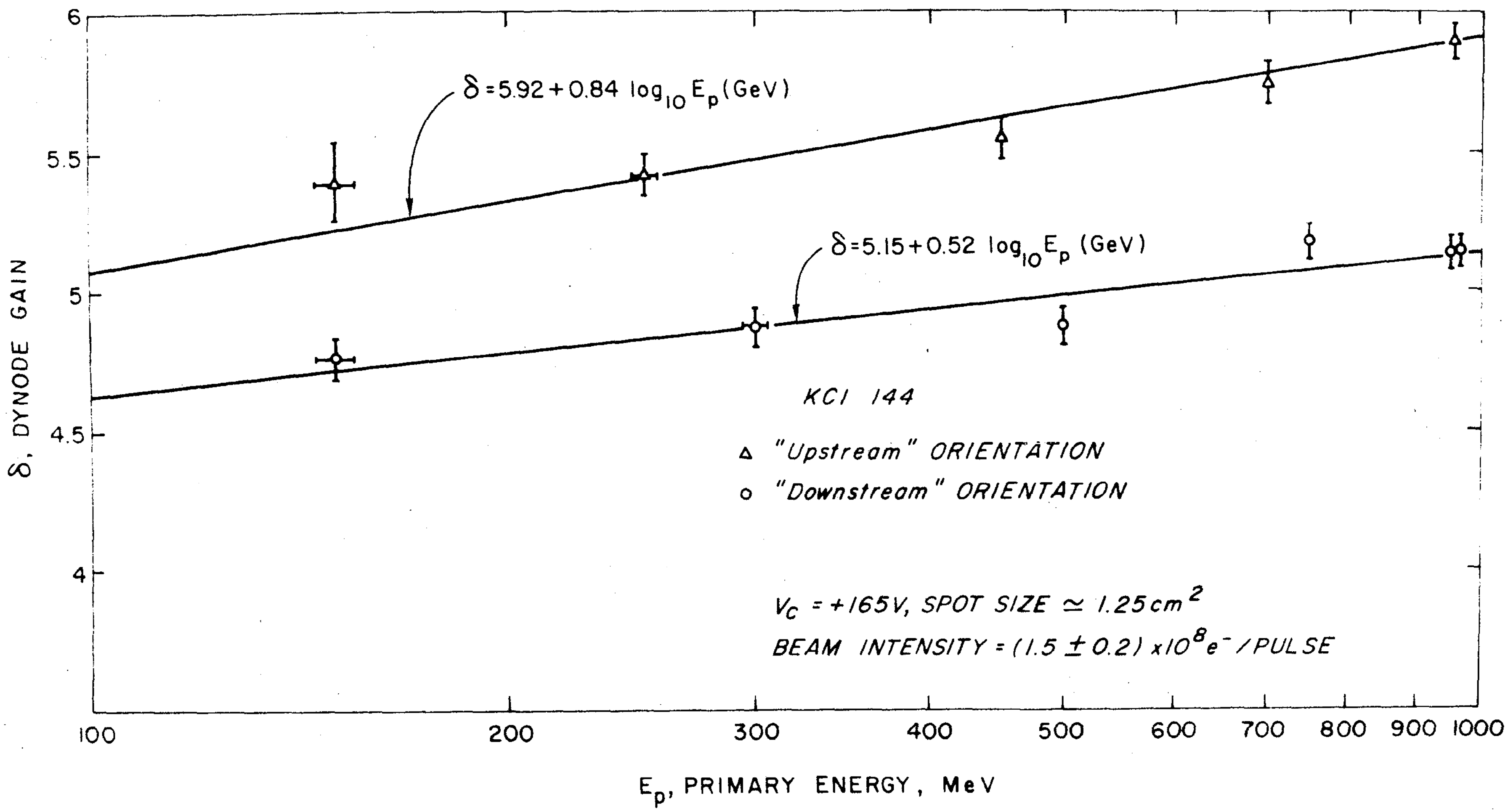
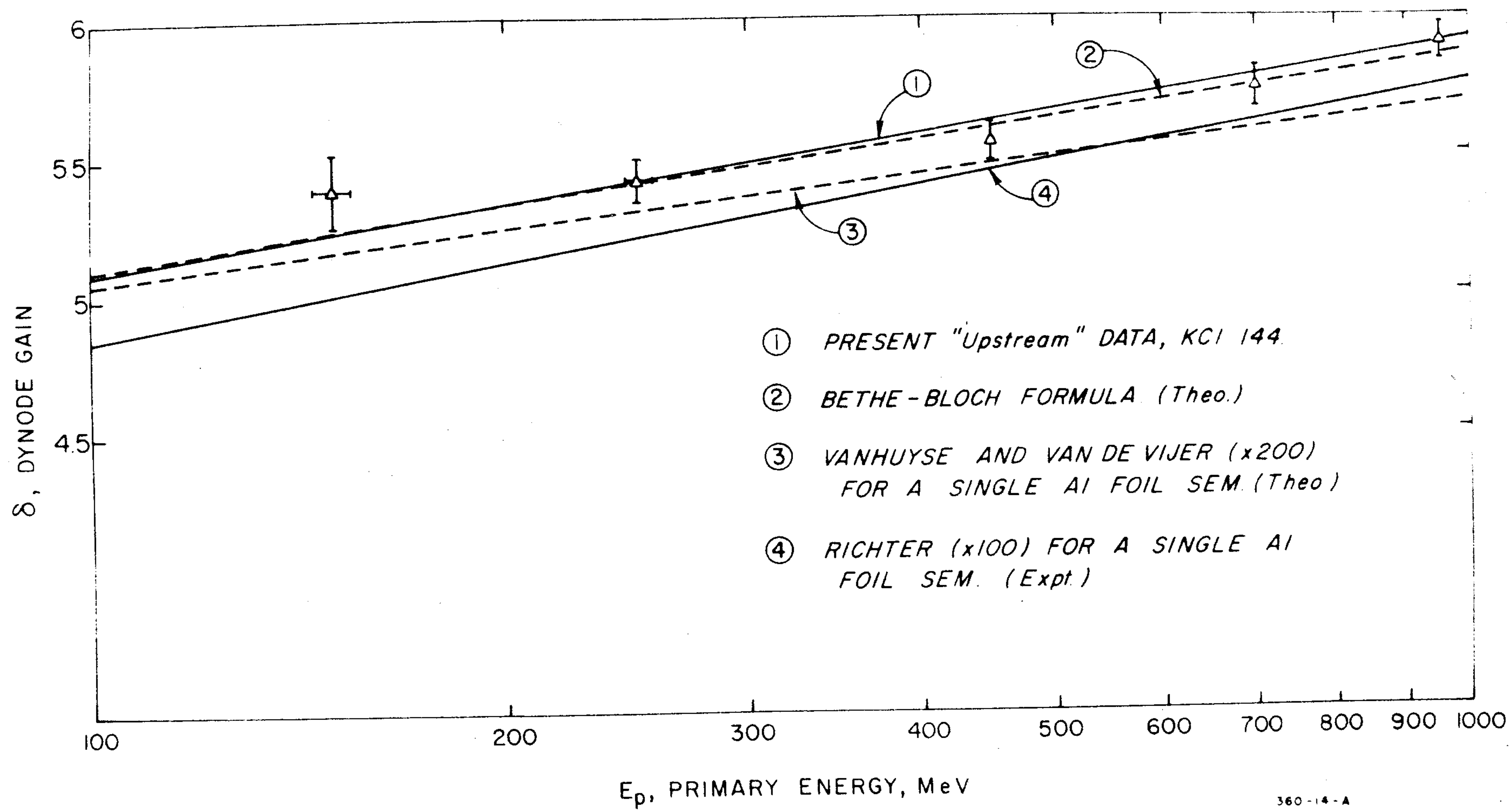
2
1


δ, DYNODE GAIN
6
5
4
3
2
10^7
10^8
10^9
10^{10}
BEAM INTENSITY, e⁻/PULSE
KCl 144
○ V_c = +200V
▲ V_c = +165V
E_p = 965 MeV
"Downstream" ORIENTATION
SPOT SIZE ≃ 1.25 cm²
360-4-8


δ=5.92+0.84 log10 Ep (GeV)
δ=5.15+0.52 log10 Ep (GeV)
KCl 144
Δ "Upstream" ORIENTATION
o "Downstream" ORIENTATION
Vc = +165V, SPOT SIZE ≃ 1.25 cm2
BEAM INTENSITY = (1.5 ± 0.2) x10^8 e⁻/PULSE
δ, DYNODE GAIN
6
5.5
5
4.5
4
100
200
300
400
500
600
700
800
900
1000
Ep, PRIMARY ENERGY, MeV
360-3-8



6
5.5
5
4.5
δ, DYNODE GAIN
① PRESENT "Upstream" DATA, KCl 144
② BETHE-BLOCH FORMULA (Theo.)
③ VANHUYSE AND VAN DE VIJER (x200) FOR A SINGLE Al FOIL SEM (Theo)
④ RICHTER (x100) FOR A SINGLE Al FOIL SEM. (Expt.)
100
200
300
400
500
600
700
800
900
1000
Ep, PRIMARY ENERGY, MeV

360-14-A