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A HIGH-PRECISION FARADAY CUP AND QUANTAMETER FOR SLAC*

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ABSTRACT

Specifications and test data are given for a 20-GeV Faraday cup and quantameter. The Faraday cup has been designed to have unity efficiency for electrons or positrons to an accuracy of better than ± 0.1% at energies up to 20 GeV. Recent data obtained with positrons as well as electrons and with secondary emission monitors, a calorimeter, and a toroid as well as ion chambers and the quantameter are consistent with those reported earlier indicating an absolute efficiency of (100.0 ± 0.2)% at energies up to 15 GeV. The quantameter was designed to have a gain linear in electron, positron, or photon energy to ± 0.1%. In tests with the Faraday cup and other monitors using electron beams at Stanford and positron and electron beams at SLAC, the quantameter has been calibrated to ± 0.3% and its linearity established to ± 0.2% at energies up to 15 GeV.

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I. INTRODUCTION

This paper consists of three parts. The first two are a review of the work done prior to January, 1967, on the SLAC Faraday cup and quantameter. This work has been described in detail elsewhere.[1] The third part of the paper summarizes the more recent test data obtained with other monitors including a secondary emission monitor, a calorimeter, and a toroid. The comparisons of beam monitor response for positrons and electrons are of particular interest. The new data are generally consistent with those published earlier: in particular, they support the previous estimate of the absolute Faraday cup efficiency, (100.0 ± 0.2)% at energies from a few hundred MeV up to 15 GeV.

II. DESIGN PARAMETERS

A. Faraday Cup

The SLAC Faraday cup is shown in Fig. 1. The scale is indicated by the copper core which is 10 inches deep and 10 inches in diameter. The thickness along the beam line is 72 radiation lengths, and the radius is 46 radiation lengths. The net loss of electrons due to shower penetration is estimated to be 0.01% or less at 20 GeV.[2,3,4] Charge losses due to μ mesons, for example to μ pairs which emit secondary electrons as they leave the cup, are expected to be well under 0.1%.

The geometry of the cup-proper is highly re-entrant to minimize the losses due to backward-going shower electrons,[4] to backscattering of primaries, and to the emission of secondary electrons in the backward direction. There is some evidence[5] that the pseudo re-entrant geometry used in the Orsay cups[6] leads to a loss of electrons amounting to about 0.2% of the incident electron or positron intensity at 500 MeV. A one-inch-thick carbon plug at the bottom is intended to reduce backscattering of primaries still further, and it may be of some use at primary energies of 100 MeV or less. The thin entrance window of the vacuum chamber is located at the end of a long and relatively narrow snout to prevent secondary electrons emitted from the window from reaching the cup. Additional discrimination against secondary emission is provided by permanent magnets installed in the snout near the entrance window and at the bottom of the cup just in front of the carbon plug. These produce a field of at least 250 gauss over a length of 3 inches, enough to trap all electrons or positrons with energies below about 1.5 MeV. At SLAC energies, the geometry alone is sufficient to reduce the effects of secondary emission and of backscattering primaries to less than 0.1%.

The Vacion pump in Fig. 1 is connected to the vacuum chamber in such a way that ions from the pump cannot reach the cup. The pressure in the cup is normally below 10^{-4} torr. The cup-proper is mounted within the vacuum chamber on four double-ceramic insulators, the two halves of which are separated by copper foil. The foils are connected to the "guard ring" surrounding the output signal. The resistance from the signal lead to the guard ring when the guard is connected to the foils is greater than 10^{14} ohms.

The SLAC Faraday cup is designed for operation at relatively high power levels. The copper core, whose thickness is about twice the length to shower maximum, permits a factor of 100 increase in the short-term power rating as compared with the corresponding cup having a lead core. The walls of the cup-proper are of unpolished black iron, and the inner and outer surfaces of the aluminum vacuum chamber are anodized black to permit a factor of 10 increase in the long-term power rating as compared with reflecting aluminum or steel walls. The calculated ratings are 100 kW and 10 kW, but for safety, we have restricted the short-term and long-term power levels to 10 kW and 1 kW, respectively. This is well below the 600-kW rating[7] of the SLAC electron beam at full power; but it is sufficient to permit tests and calibrations of the high-intensity SLAC toroids[8] over a significant intensity and energy range.

B. Quantameter

The SLAC quantameter is shown in Fig. 2. Conceptually the design follows closely the one adopted originally by Wilson,[9] although the actual dimensions are different. The plate spacings of 1/8 inch and 1/4 inch were maintained by individually grinding the steel spacers during assembly. The average spacing is thus (0.476 ± 0.003) cm instead of 0.150 cm for the 1-mm and 2-mm gaps used by Wilson. The Simpson's method integration is, of course, valid in either case; but it is not important at high energies with a large number of gaps. To permit direct calibrations with incident electrons or positrons, we have included a first gap of 1/16 inch. The corresponding gap is omitted by Wilson as it is superfluous with incident photons. The average thickness of the copper plates is (0.963 ± 0.003) cm instead of 1 cm, and there are 28 plates instead of 12 used by Wilson. The radii of the collector and high-voltage plates are 6 inches and 7-1/8 inches, respectively. A copper screen supported by the edges of the larger plates, together with the different radii chosen for the two kinds of plates, defines the extra radial volume necessary to "compensate" for radial shower penetration. Similarly, the last two gaps of 9/16 inch and 1/4 inch separated by a thin sheet of copper are equivalent to a single gap of 3/4 inch, plus 1/16 inch, the latter being the last gap of the Simpson's integration and the former being the appropriate spacing for longitudinal "compensation." For convenience, a thin-foil ion chamber has been added in front of the quantameter.

The various dimensions, while different from those chosen by Wilson, are nevertheless sufficiently well-known to permit an accurate comparison with other quantameters when the standard 95% argon-5% CO_2 gas mixture is used. From the data of Wilson with the corrections noted in Ref. 10, the "quantameter constant" was calculated to be $(1.440 \pm 0.010) \times 10^{18}$ MeV/coulomb at 800 mm Hg and 20° C, where the error includes only the uncertainties in plate thickness and density and in plate spacing.

In estimating the linearity, we note first that the calculated radial energy losses due to shower penetration are only about 0.1% at 20 GeV.[4] Any success at all for the radial compensation will make this negligible. Longitudinally, we expect to lose 0.6 to 0.8% of the energy at 1 GeV and 1.8 to 2.4% of the energy at 20 GeV.[4] The linearity without compensation would thus be 1.2 to 1.6% over this range. If the compensation is effective to within 5% of the total energy loss, then the nonlinearity is of order 0.06 to 0.08% $\lesssim$ 0.1%.

Two gases have been used in the quantameter at various times, namely, hydrogen and the standard 95% argon-5% CO_2 mixture. Hydrogen is normally used in relatively intense beams, while argon-CO_2, with an order of magnitude higher gain, is more suitable for low intensities such as are used in the photoproduction experiments being done in the two-meter streamer chamber. In either case, the gas flows through the quantameter at ambient temperature and pressure. Under these circumstances, the composition of the gas does not change with time;[11,12] and the small corrections for temperature and pressure can easily be made with a precision of better than 0.1%. It is perhaps worth noting that the ambient temperature in End Station A at SLAC, where most of the tests were carried out, is normally constant to within 2° or 3° C during any 24-hour period. Thus thermal equilibrium effects of the type observed at Caltech[13] should be of the order 0.1% or less, providing that less than about 1 W average power is incident upon the quantameter. This corresponds to about 10^{6} electrons per pulse, 360 cycles per second at 20 GeV.

III. EARLY TEST DATA

A. General Remarks

The earliest beam monitor tests at SLAC were carried out jointly with the Faraday cup and quantameter just described, using hydrogen-filled ion chambers as non-beam-destructive reference monitors.[1,5,14] The high gain of the ion chambers permits tests of the quantameter at low intensities where toroids and secondary emission monitors are no longer practical. The stability and reproducibility over long periods of time are excellent, while the gain is independent of intensity over a fairly wide range.

Two types of "slideback" current integrators were used interchangeably in the beam monitor tests. The first was designed by Carl Olson and has been used for many years at Stanford. The second consists of a commercial electrometer, the Cary 31, with precision input capacitors added. This type has also been used for many years at Stanford and elsewhere.

There is a certain amount of lore associated with the monitoring of low intensity beams. Certain procedures, such as measuring the integrator zeros before each integration and measuring the "leakage" currents before and after the integrations, are common practice. Cables and integrators are always carefully checked before each run, and leakage currents are normally less than 10^{-13} A. Various tests insure that the nonlinearity of the integrators and the uncertainties in the relative capacitor values are somewhat less than $\pm$ 0.1%. Every effort is made to hold the "fixed" parameters as nearly constant as possible. Within the limits of accelerator stability on a pulse-to-pulse basis, this includes the beam intensity and radial distribution, the integration period, and the final integrated voltages.

The tests reported here always depend upon measurements of the ratio of two quantities, such as the ion chamber and Faraday cup outputs, under a particular set of experimental conditions. The measurements are then repeated with slightly different conditions, and an error is assigned on the basis of the variations observed in a number of integrations for each set of conditions. Unless otherwise specified, the error assigned to a given measurement is purely statistical and has the significance of one standard deviation from the mean. The object is to determine whether a systematic effect exists that is larger than the assigned error.

The logical argument upon which the early tests were based may be stated as follows: 1. There is a Stanford Faraday cup whose efficiency is believed, on the basis of experimental tests,[14] to be $(100.00 \pm 0.15)\%$ at energies from 200 to 850 MeV. 2. The SLAC and Stanford Faraday cups have the same efficiency at 850 MeV. 3. The response of the SLAC cup is independent of energy in the range from 1 GeV $\sim$ 850 MeV to 15 GeV. The conclusion is that within the assigned errors, the absolute efficiency of the SLAC Faraday cup is known at energies up to 15 GeV. The experimental tests are summarized in the remainder of this section.

B. Low-Energy Tests

The effect of an imperfect vacuum in the Faraday cup was tested with electrons at 200 MeV by comparing (ion chamber gain)/(Faraday cup efficiency) = IC/FC at 150×10^{-4} torr and 300×10^{-4} torr. The efficiency of the cup decreased by 2.8%, or about 0.02% per 10^{-4} torr. This agrees in order of magnitude with preliminary estimates. The effect is negligible at SLAC Faraday cup pressures. Since the secondary charge leaving the cup is a very small fraction of the primary charge entering, the effect should be independent of energy.

Secondary emission from the entrance window of the Stanford Faraday cup was investigated in Ref. 14 by establishing a weak transverse magnetic field between the entrance window and the cup as well as by placing a grid behind the entrance window and biasing it to return low-energy secondary electrons to the window. In each case, all electrons of less than a few hundred eV were prevented from reaching the cup. Similarly, the effect of secondary emission from the cup-proper was evaluated with a grid placed near the bottom of the cup and biased to return all electrons with energy below 500 eV to the cup. With incident electrons, the enhanced efficiency due to emission from the window was found to be $\left(+\,0.05\,{}^{+\,0.06}_{-\,0.05}\right)\%$. The error was calculated from the variations in a number of repeated measurements and takes into account the intrinsic sign of the effect being tested. The change due to backwardgoing secondaries was $\left(-\,0.02\,{}^{+\,0.02}_{-\,0.06}\right)\%$. The net result of the low-energy effects including ionization was $\left(+\,0.03\,{}^{+\,0.08}_{-\,0.08}\right)\%$.

The "front-end" of the SLAC Faraday cup is quite similar to that of the Stanford cup except that the geometry is more re-entrant, the snout is somewhat longer, and the magnets are rather stronger. Without further measurements, we reason that the secondary-emission data for the Stanford cup provide a reliable upper limit on the effect of secondary emission for the SLAC cup. We would further argue at this point that if energy-dependent effects such as shower penetration are negligible, both cups must have unity efficiency within the uncertainties of the low-energy tests.

As a final test of the low-energy effects, we have compared the SLAC and Stanford cups at 850 MeV using various ion chambers as reference monitors. At the same time we have tested a new Stanford cup which is identical to the old one except that it has a greater longitudinal thickness of lead to make up for the 8-inch-thick iron plate added to the back of the old cup when it was modified for use at energies above 300 MeV.[14] The relative efficiencies observed with a 1-cm-diameter beam spot were

$$\left(FC_{NEW} - FC_{SLAC}\right)/FC_{SLAC} = (-\ 0.08 \pm 0.10)\%,$$
$$\left(FC_{OLD} - FC_{SLAC}\right)/FC_{SLAC} = (-\ 0.31 \pm 0.09)\%,$$
$$\left(FC_{OLD} - FC_{NEW}\right)/FC_{NEW} = (-\ 0.23 \pm 0.12)\%.$$

As usual, the errors have been calculated from the variations in a number of repeated measurements. While the (- 0.31 ± 0.09)% difference in the apparent efficiencies of the SLAC and the old Stanford Faraday cups may be significant, the excellent agreement between the SLAC cup and the new Stanford cup suggests that it is not. In any case, we interpret the comparisons of the SLAC and Stanford cups as providing the desired check that at low energies the efficiency of the SLAC cup is (100.03 ± 0.08)%, the result indicated by the low-energy tests.

C. Ion Chamber Versus Faraday Cup

In Fig. 3 we have plotted theoretical[15] curves for the specific ionization (i.e., the ionization per atom normalized to 1.00 at 1 atm and 10 GeV) as a function of energy for hydrogen gas at 1 and 2 atm. The important feature is that after reaching a minimum at a few MeV, the ionization increases monotonically ("relativistic rise") until, at an energy of order 100 MeV, it becomes constant. Furthermore, the relativistic rise is less pronounced and terminates at a lower energy for 2 atm than for 1 atm ("density effect"). For liquid hydrogen, the magnitude of the theoretical relativistic rise is only a few percent.

Shower penetration in the case of a Faraday cup leads to a net loss of electrons. The penetrating particles are predominantly low-energy gammas accompanied by a lesser number of positron-electron pairs and Compton electrons. Thus with electrons incident, the Faraday cup efficiency decreases with energy or is constant, and the ratio IC/FC either increases with energy or is constant.

If IC/FC increases with energy, we don't know which monitor to blame. If IC/FC is constant with energy, we assume that both monitors are constant. A fortuitous cancellation is precluded by the respective signs of any variation in IC or FC.

The data from Stanford[14] and Orsay[5] on the "energy dependence of the ionization of hydrogen gas" are summarized in Fig. 4, along with unpublished measurements made at Stanford[16] with a second Stanford Faraday cup of a different design.[17] In each case, the data at 1 atm have been normalized to unity at 850 MeV, while the data from Ref. 14 at 2 atm have been normalized to 0.968 at the same energy. These values were taken from Fig. 3; they have no experimental significance and are used only as a convenient way of distinguishing the 1-atm and 2-atm results plotted on the same graph. The error bars indicate the standard deviation of the mean for a number of measurements of the ratio at a given energy setting.

The combined data at 1 atm with 3 different Faraday cups give a net "relativistic rise" of (+ 0.37 ± 0.05)%. The result at 2 atm from Ref. 14 is (- 0.03 ± 0.11)%. A more recent comparison[1] of the energy dependence at 1 atm with that at 2 atm yielded (+ 0.38 ± 0.04)% over the range from 200 to 900 MeV: this, together with the 1-atm data, yields an independent measurement of (- 0.01 ± 0.07)% for the energy dependence at 2 atm, in excellent agreement with the 2-atm data from Ref. 14. The theoretical curves shown in Fig. 3 based on Ref. 15 agree qualitatively with experiment but predict a somewhat lower energy for the termination of the relativistic rise at 1 atm.

The data on IC(2 atm)/FC versus energy, together with the low-energy tests, complete the evaluation of the Stanford Faraday cup reported in Ref. 14 and yield an absolute efficiency of (100.00 ± 0.15)%. Since the early termination of the relativistic rise in hydrogen at 2 atm seems well established, it was hoped that a measurement of IC(2 atm)/FC would place a small limit on the energy dependence of the SLAC Faraday cup at high energies. The results are shown in Fig. 5. Surprisingly, they indicate an increase of (1.09 ± 0.12)% in going from 1.1 to 14.3 GeV. This increase, while small by some standards, is in striking disagreement with the theoretical expectations as well as with any reasonable extrapolation of the 2-atm measurements as less than 1 GeV. Furthermore, no change was observed in the ratio IC(1 atm)/IC(2 atm) over this energy range.

The high-energy tests described in the next section indicate specifically that the energy dependence observed in IC(2 atm)/FC does not result from a loss of charge by the Faraday cup. Only one explanation is consistent with all of the data: shower penetration of low-energy gamma rays from the A-Beam Switchyard, where all but a few percent of the primary beam from the accelerator was stopped in the collimators and the narrow (i.e., < 0.1%) momentum slits. Further evidence was provided by the positive identification of low-energy photons by their characteristic attenuation in a 1-m LiH beam hardener. A final test with the quantameter, which is insensitive to low-energy photons, provided a precise evaluation of the Faraday cup efficiency versus energy.

D. Specific High-Energy Tests

Shower penetration out the back and sides of the SLAC Faraday cup were studied at 15 GeV with ion chambers placed at these locations. The results, interpreted conservatively, yield a limit of 0.2% for the longitudinal penetration and 0.1% for the radial component. The same tests yield a limit of 0.1% for penetrating muons arriving with the incident beam or produced in the cup. A limit of 0.001% can be placed on the change in Faraday cup efficiency resulting from muon pairs which eject electrons as they leave the cup.

The quantameter ion chamber, which is 5 inches in diameter and located only 4 inches from the first plate of the quantameter, yielded an energy dependence of $(3.46 \pm 0.25)\%$, some 2% larger than for the 1- and 2-atm chambers. This difference is evidently due to backward-going ionizing radiation. The spurious ionization from this source would change IC(2 atm) in the ratio IC(2 atm)/FC by only 0.03%. The result can also be used to infer an upper limit on the charge leaving the copper core of the Faraday cup in the backward direction. The re-entrant geometry reduces the solid angle by a factor of at least 20 and gives about 0.1% if the radiation is isotropic and if all of the ionization is due to backward-going electrons (e.g., to backscattered primaries or to shower electrons). These tests, at 15 GeV, together with the low-energy data, are sufficient to place limits of a few tenths of a percent on the absolute Faraday cup efficiency.

A conclusive test for low-energy gamma rays was obtained on a photon beam run. With the photon radiator out of the electron beam, but with the collimated and momentum-analyzed primary beam of electrons being "dumped" in a beam dump located in the switchyard, the ion chambers indicated a background of 10^{-2} of the intensity obtained with the radiator in the beam. The background decreased to 5×10^{-5} when a 1-m LiH beam hardener (1.86×10^{23} electrons/cm^2) was put into the photon beam. This corresponds to a total gamma-ray-attenuation cross section of 2.7×10^{-25} cm^2/electron in the LiH hardener and is characteristic of gammas of about 0.6 MeV.* The quantameter data also indicated a background of quite low energy.

*We are grateful to Dr. R. C. McCall for pointing out this interpretation of the beam hardener results.

E. Quantameter Versus Faraday Cup

The experimental data on the energy dependence of (quantameter gain/energy)/ (Faraday cup efficiency) = (Q/E)/FC are plotted in Fig. 6. This ratio is expected to be independent of energy in spite of the low-energy gammas which evidently accompany the beam. The Faraday cup is insensitive to neutrals, and the quantameter is insensitive to gamma radiation having only about 0.6 MeV/15 GeV ~ 0.004% of the energy of the incident beam and having an intensity comparable to the primary beam intensity. One might be concerned that some fraction of the spurious ionization detected by the ion chamber (resulting presumably from Compton electrons produced by the low-energy gammas) would enter the Faraday cup and given an efficiency for electrons greater than unity, but the entrance magnets and long snout should reduce such an effect considerably.

The results obtained at 1.0092 and 15.000 GeV are plotted in Fig. 6 for the first run, along with measurements at 15.000 GeV from a second run. In each case, the energy was defined by the computer-controlled magnets of the A-Beam Switchyard. Also shown are data obtained at Stanford with the "9-foot" and "15-foot" momentum-analyzing systems. The Stanford data are expected a priori to be less precise than the SLAC results since the incident energy was not known to be better than 1% at the time of these tests. The energy determination at SLAC was assumed to be uncertain by ± 0.2%, the value given in the SLAC Users Handbook, but it now appears[18] that ± 0.4% is a more realistic estimate for the 1-GeV point of Ref. 1.

The first run at SLAC gave (423.2 ± 0.3) ions per GeV at 1 GeV and (424.2 ± 0.6) ions per GeV at 15 GeV with hydrogen gas corrected to 30.00 inches Hg and 300° K. The energy dependence indicated by the first run was thus (+ 0.24 ± 0.17)%. The second run gave (422.0 ± 1.0) ions per GeV and an energy dependence of

(- 0.28 ± 0.26)%. The combined result for the energy dependence in the range from 1 to 15 GeV was (- 0.07 ± 0.15)%, while the mean "quantameter gain" measured at SLAC was (423.1 ± 0.3) ions per GeV. The average of the Stanford meassurements was (422.6 ± 2.8), which differs from the value at SLAC by (+ 0.12 ± 0.66)%. The quantameter constant measured at 16 GeV with the standard 95% argon-5% CO_2 mixture, corrected to 800 mm Hg and 20^{o} C, is $(1.389 \pm 0.004) \times 10^{18}$ MeV/coulomb. Allowing for systematic errors, this is about (3.6 ± 0.8)% lower than the predicted value, and in this respect, it is similar to the values found at other laboratories.[10,19,20]

If the uncertainties in energy are neglected and only the "statistical" errors included, then the energy dependence of (Q/E)/FC leads to an estimate of the apparent Faraday cup efficiency at 15 GeV of 100.00% - (0.07 ± 0.15)% + (0.03 ± 0.06)% = (99.96 ± 0.17)%. This estimate of Ref. 1 is compared with more recent data in a later section.

F. Radial Dependence of Faraday Cup and Quantameter Efficiency

The radial dependence of the Faraday cup efficiency was tested at 15 GeV by moving the Faraday cup horizontally through the beam. The results for FC/IC normalized to unity are shown in Fig. 7 for a beam spot of 1-inch diameter. The data indicate that for a point spot the efficiency is independent of position to ± 0.2% within the 5-inch entrance aperture and hole diameter. The nominal center is - 0.37 inch away from the true center due to errors in beam alignment, a fact which is of no importance for the other tests.

The radial-dependence data for the quantameter are plotted in Fig. 8, again for a 1-inch beam spot at 15 GeV. The response is flat to about 0.2% over a 3-inch diameter region and declines by about 3% when the beam strikes the entrance flange and the rings of the quantameter ion chamber.

G. Quantameter Saturation

Studies of quantameter saturation, an effect which results from the recombination of the ions in the gas, are shown in Fig. 9 both for hydrogen and for the standard argon-CO_2 mixture at 15 and 16 GeV, respectively. In each case, the gas was flowing through the quantameter at ambient temperature and pressure at a rate of about 1 volume per 2 hours. Previously the quantameter was pumped out and filled several times in succession. The high voltage was set at - 1000 volts, equivalent to about - 330 volts for the Wilson quantameters which have 1/3 smaller spacings between plates. The gain is independent of intensity up to $1 - 2 \times 10^7$ particles per cm^2 per 1.5 μsec pulse for hydrogen and up to $3 - 6 \times 10^5$ particles per cm^2 per pulse for argon-CO_2. The DESY results[20] at 5 GeV with argon-CO_2 give about 10^8 particles per 200 μsec pulse or about 5×10^5 particles per μsec, which is similar to the limit reported here. Saturation curves for the ion chambers resemble those obtained with the quantameter except that the flat response region for hydrogen typically extends well above 10^8 particles per cm^2 per μsec pulse.

III. RECENT TEST DATA

A. Faraday Cup Versus Calorimeter and Toroid

The agreement within errors of 1-2% of the quantameter constant measured at SLAC with values measured elsewhere is in some sense a direct test of the absolute efficiency of the Faraday cup, as well as of the absolute energy of the A-Beam Switchyard. Independent data of a similar nature have recently been obtained by G. Fischer[21] using a calorimeter and by R. Larsen[8] using a self-calibrating toroid. The calorimeter result, expressed as C/FC and measured with electrons at 10 GeV, agrees with the calculated ratio within (- 0.14 ± 0.5)%. As usual, the error given is purely statistical.

The toroid data expressed as T/FC differ from the quantameter and calorimeter results in that the toroid was about 52 feet upstream of the cup. Since the toroid itself is the subject of a separate paper to be given at this conference, we shall mention only that the average of 30 empty-target integrations taken with positrons (five beams and two energies) and with electrons (four beams and two energies) last September was

$$T/FC = 1.0015 \pm 0.0015 .$$

B. Positron-Electron Comparisons

Extensive measurements of the ratio IC/FC were made at 300 MeV at Stanford[14, 16] for both positrons and electrons in the course of scattering experiments. The result was

$$\Delta(IC/FC) \equiv \frac{IC/FC(\text{positrons}) - IC/FC(\text{electrons})}{IC/FC(\text{positrons}) + IC/FC(\text{electrons})}$$

$$= (+\,0.005 \pm 0.055)\% .$$

Since the Faraday cup efficiency was known to be $(100.00 \pm 0.15)\%$ from the tests already described, the ion-chamber data established the equality of the specific ionization of positrons and electrons in hydrogen to $\pm\, 0.3\%$.

Once the equality of the ionization for positrons and electrons is known experimentally, it can be used directly as a test of the efficiency of other Faraday cups.[5] It is a particularly convincing test since all of the factors expected to affect the intrinsic Faraday cup efficiency, except for backscattering of primaries, have opposite sign for positrons and electrons. In particular, it is plausible to assume that the efficiency for electrons is $(100.00 + \Delta(IC/FC))\%$, while the efficiency for positrons is $(100.00 - \Delta(IC/FC))\%$.

More generally, any reference monitor which has the same efficiency for positrons and electrons could be used to test Faraday cup efficiency. Furthermore, if a number of different monitors give the same result, this value could reasonably be associated with the Faraday cup even if the "reversibility" of none of the reference monitors has been established independently. Our intention here is not so much to prove anything; rather we hope to bring to bear as much information as possible on the question of absolute Faraday cup efficiency.

The quantameter gain for hydrogen measured with positrons at 10 GeV some six months after the tests reported in Ref. 1 was (424.6 ± 1.2) ions per GeV. The difference in the 10-GeV positron and 15-GeV electron data is (+ 0.24 ± 0.31)% corresponding to a value

$$\Delta((Q/E)/FC) = (+\,0.12 \pm 0.16)\%$$

and an apparent Faraday cup efficiency for electrons of

$$\eta_{FC} = (1.0012 \pm 0.0016)\% \text{ at } 10 - 15 \text{ GeV}.$$

Among other things, this result is indicative of the reproducibility of (Q/E)/FC at SLAC over long periods of time.

In Fig. 10a the ratio (SEM/FC) obtained by the positron-scattering group at SLAC[22] is plotted as a function of target thickness for both positrons and electrons at 10 GeV. The material, consisting mostly of copper with some aluminum, was added 35 feet upstream of the six-inch SEM, which in turn was located just in front of the Faraday cup. The general increase in (SEM/FC) with the square of the target thickness seems to be the result primarily of bremsstrahlung followed by pair production. (The pairs are detected by the SEM but add zero net charge to the Faraday cup.) The difference in the positron and electron curves shown in Fig. 10b also varies experimentally as the square of the target thickness and is consistent in order of magnitude with bremsstrahlung followed by Compton scattering. (The Compton electrons add to the SEM and Faraday cup readings with incident electrons, but they subtract from the apparent Faraday cup efficiency with incident positrons.)

Similar measurements of (SEM/FC) taken with a three-inch SEM located upstream of the target indicate a much sharper increase with target thickness than is shown in Fig. 10a, but the results for Δ are remarkably similar to those plotted in Fig. 10b. This is consistent with the idea that the variation in Δ with target thickness is associated with the Faraday cup and presumably with Compton electrons. If the dependence of Compton scattering and bremsstrahlung on the target element is taken into account, the experimental correction in Δ is - 0.04% at 10 GeV and - 0.06% at 4-5 GeV for the 0.025 radiation lengths of air and aluminum in the empty-target geometry of the positron scattering experiments. The correction is negligible for the monitor tests of Ref. 1 as well as for the measurement of ((Q/E)/FC) with incident positrons.

The combined (SEM/FC) data for the two secondary emission monitors and three electron-positron reversals corrected to zero target thickness yields the value

$$\Delta(\mathrm{SEM/FC}) = (+\ 0.05 \pm 0.05)\% \text{ at 4-5 GeV} .$$

The value for two secondary emission monitors and two reversals is

$$\Delta(\mathrm{SEM/FC}) = (+\ 0.13 \pm 0.09)\% \text{ at 10 GeV} .$$

Similar data for the SLAC toroid and seven electron-positron reversals yields

$$\Delta(\mathrm{T/FC}) = (+\ 0.19 \pm 0.07)\% \text{ at 4-5 GeV} ,$$

and for five reversals yields

$$\Delta(\mathrm{T/FC}) = (+\ 0.17 \pm 0.09)\% \text{ at 10 GeV} .$$

The data relating to the <u>apparent</u> efficiency of the SLAC Faraday cup are collected as a function of energy in Fig. 11. Included are: 1. the low-energy test data plotted at 850 MeV where the comparison of SLAC and Stanford Faraday cups was made; 2. the apparent Faraday cup efficiency at 15 GeV derived from the low-energy test data and the energy dependence of (Q/E)/FC; 3. the apparent efficiency indicated by $\Delta((Q/E)/FC)$; 4. the apparent efficiency indicated by $\Delta(SEM/FC)$; and 5. the apparent efficiency indicated by $\Delta(T/FC)$. The high-energy test data are indicated by a lower limit on the loss of charge from the cup, which we assume to be predominantly negative. Finally, we have included the result of Ref. 14 on $\Delta(IC/FC)$ at 300 MeV, which is relevant since the SLAC and Stanford cups are believed to have the same efficiencies at low energies.

The various indications of the performance of the SLAC Faraday cup are remarkably consistent and are in good agreement with the $(100.0 \pm 0.2)\%$ estimate of Ref. 1. If anything, the new data suggest an efficiency for electrons at high energies that is 0.1 - 0.2% above 100%. Such an effect, if it exists, could be caused by Compton electrons accompanying a beam contamination of low-energy gamma rays. Future tests may be carried out specifically to check this point. While the beam-monitor data indicate no energy discrepancies, it would be useful to carry out additional tests of the energy-linearity of the quantameter, taking advantage of recent refinements in the energy determination of the A-Beam Switchyard. Finally, within the appropriate limits, the new data seem to indicate that each of the monitors tested has the same efficiency for positrons and electrons.

ACKNOWLEDGMENTS

In addition to the material of Ref. 1, this article contains unpublished beam-monitoring data accumulated by several groups of physicists at SLAC. We are particularly grateful to Dr. Herbert DeStaebler, Professor Jerome Pine, and the rest of the positron-scattering group for permission to quote their extensive results comparing the efficiencies of various monitors with positrons and electrons. Dr. G. Fischer contributed useful discussions of the calorimeter and other monitor data accumulated during photoproduction experiments on the 20-GeV spectrometer. Dr. D. Drickey of the streamer-chamber group participated in the Faraday cup and quantameter tests both at Stanford and at SLAC. Raymond Larsen of the Technical Division has kept us diligently informed of the progress made with the toroid during the past two years. Finally, it is a pleasure to acknowledge the support and encouragement of Professor R. Mozley and the generous help of the accelerator staff at Stanford and at SLAC.

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LIST OF FIGURES

1. Schematic diagram of the 20-GeV Faraday cup. The scale is indicated by the copper core which is 10 inches deep and 10 inches in diameter.
2. Schematic diagram of the 20-GeV quantameter. The scale is indicated by the collector plates which are 12 inches in diameter. A thin-foil ion chamber is mounted just behind the entrance window.
3. Specific ionization in hydrogen versus energy. The theoretical curves for 1 and 2 atm were obtained from Eq. 31 of Ref. 15 and were normalized to give a value of 1.00 for 1 atm at 10 GeV.
4. Specific ionization in hydrogen versus energy. The normalized experimental data at 1 and 2 atm from Refs. 5, 14 and 16 are shown as well as the more recent data of Ref. 1 comparing the ionization at 1 and 2 atm without a Faraday cup. The normalization from Fig. 3 is used as a convenient way of distinguishing the 1-atm and 2-atm points but has no experimental significance. Straight lines have been fitted to the data to guide the eye.
5. Change in percent in the ratio of ion chamber gain to Faraday cup efficiency as a function of energy. The solid curve is from Eq. 8 of Ref. 2 for an absorber of 48 radiation lengths, while the dashed curve is for the 72-radiation-length Faraday cup. The excellent fit of the 48-radiation-length curve to the data suggests spurious ionization accompanying shower-penetration gamma rays of about 1 MeV contaminating the momentum-analyzed primary beam.
6. Quantameter gain per GeV versus energy. The ratio of (quantameter gain/energy)/(Faraday cup efficiency) = (Q/E)/FC is plotted for the electrons from the "9-foot" and "15-foot" momentum-analyzing systems at Stanford as well as from the A-Beam Switchyard at SLAC. The fluctuations in the Stanford

points are believed to be due to uncertainties in the incident energy estimated a priori to be ± 1%. A recent positron point at 10 GeV has been added to the figure published originally in Ref. 1.

7. Relative Faraday cup efficiency versus position at 15 GeV. The beam spot was 1 inch in diameter. Points taken on both sides of the cup are reflected about the experimental center at - 0.37 inch as a test of the expected radial symmetry.

8. Relative quantameter efficiency versus position at 15 GeV. The diameter of the beam spot was again 1 inch.

9. Relative quantameter efficiency versus intensity. Data are shown both for hydrogen and for the standard argon-CO_2 mixture flowing at ambient temperature and pressure.

10. In (a) the ratio (SEM/FC) obtained by the positron-scattering group at SLAC is plotted as a function of target thickness for both positrons and electrons at 10 GeV. The difference in the two curves is plotted in (b). The difference is expected to vary as the square of the target thickness if it results from bremsstrahlung followed by Compton scattering. The separate curves for positrons and electrons in (a) are also expected to vary as the square of the target thickness if this variation is the result of bremsstrahlung followed by pair production and by Compton scattering.

11. Data relating to the <u>apparent</u> efficiency of the SLAC Faraday cup. The various tests are remarkably consistent and are in good agreement with the (100.0 ± 0.2)% efficiency estimate of Ref. 1.

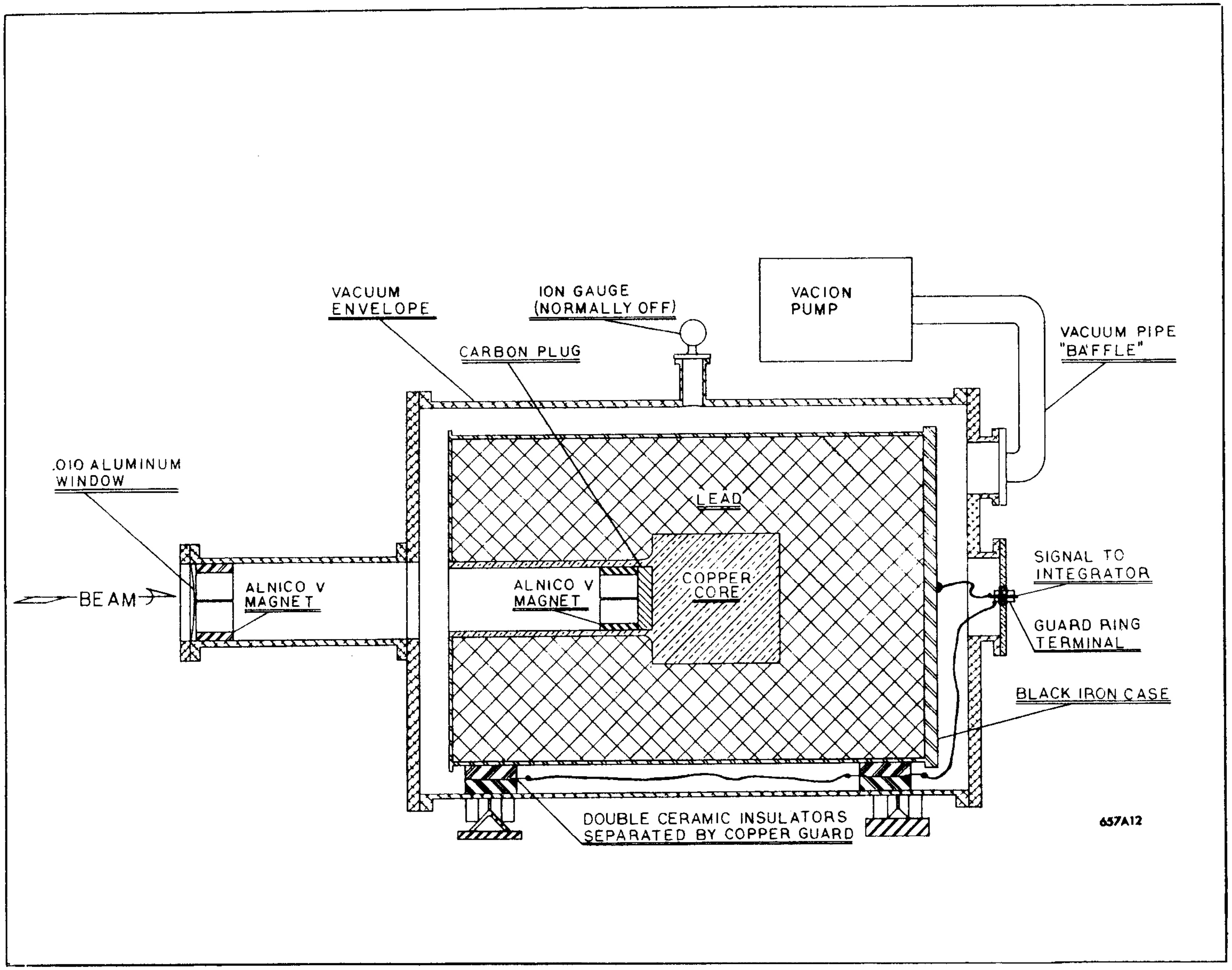

VACUUM
ENVELOPE
ION GAUGE
(NORMALLY OFF)
VACION
PUMP
VACUUM PIPE
"BAFFLE"
CARBON PLUG
.010 ALUMINUM
WINDOW
LEAD
BEAM
ALNICO V
MAGNET
ALNICO V
MAGNET
COPPER
CORE
SIGNAL TO
INTEGRATOR
GUARD RING
TERMINAL
BLACK IRON CASE
DOUBLE CERAMIC INSULATORS
SEPARATED BY COPPER GUARD
657A12

Fig. 1

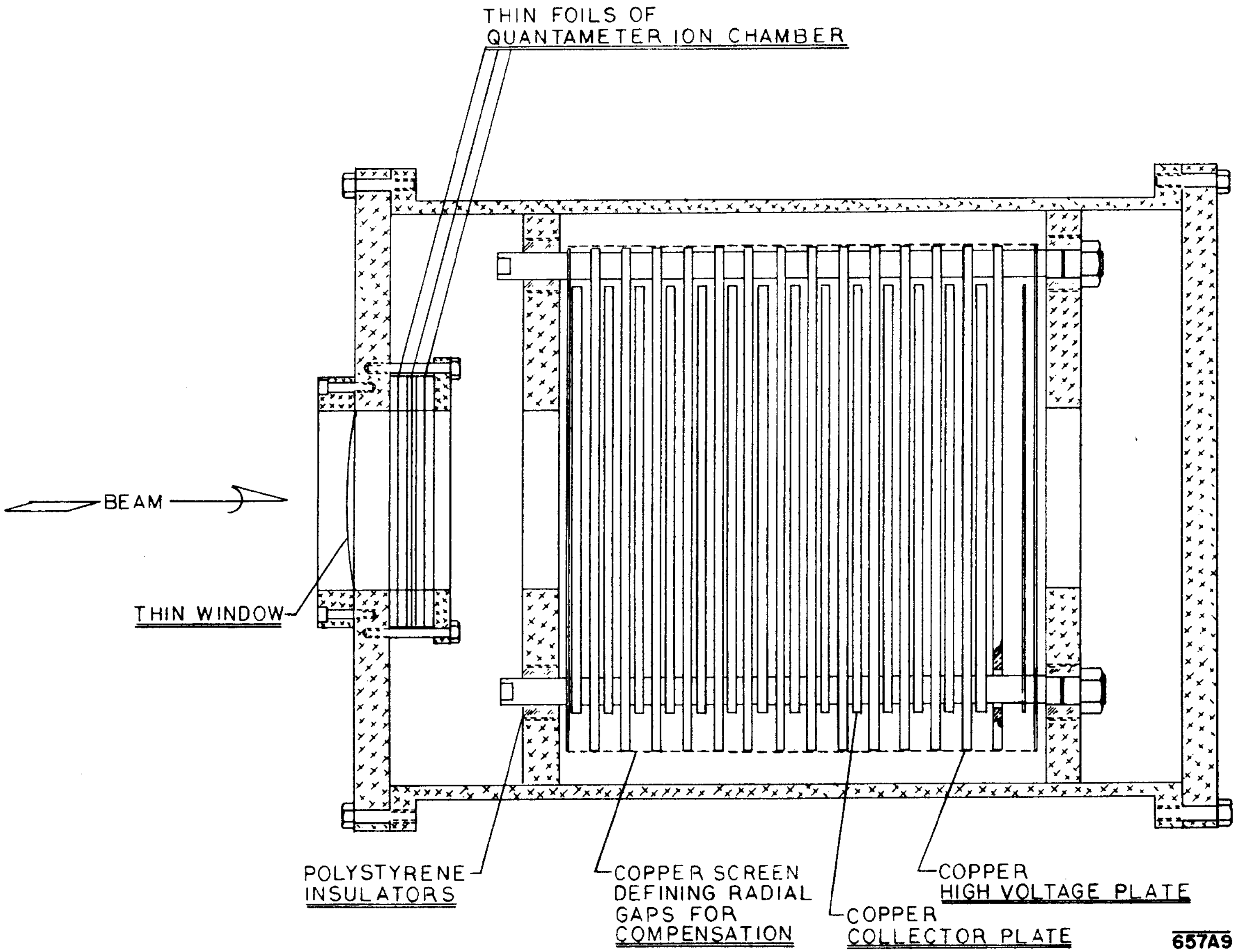
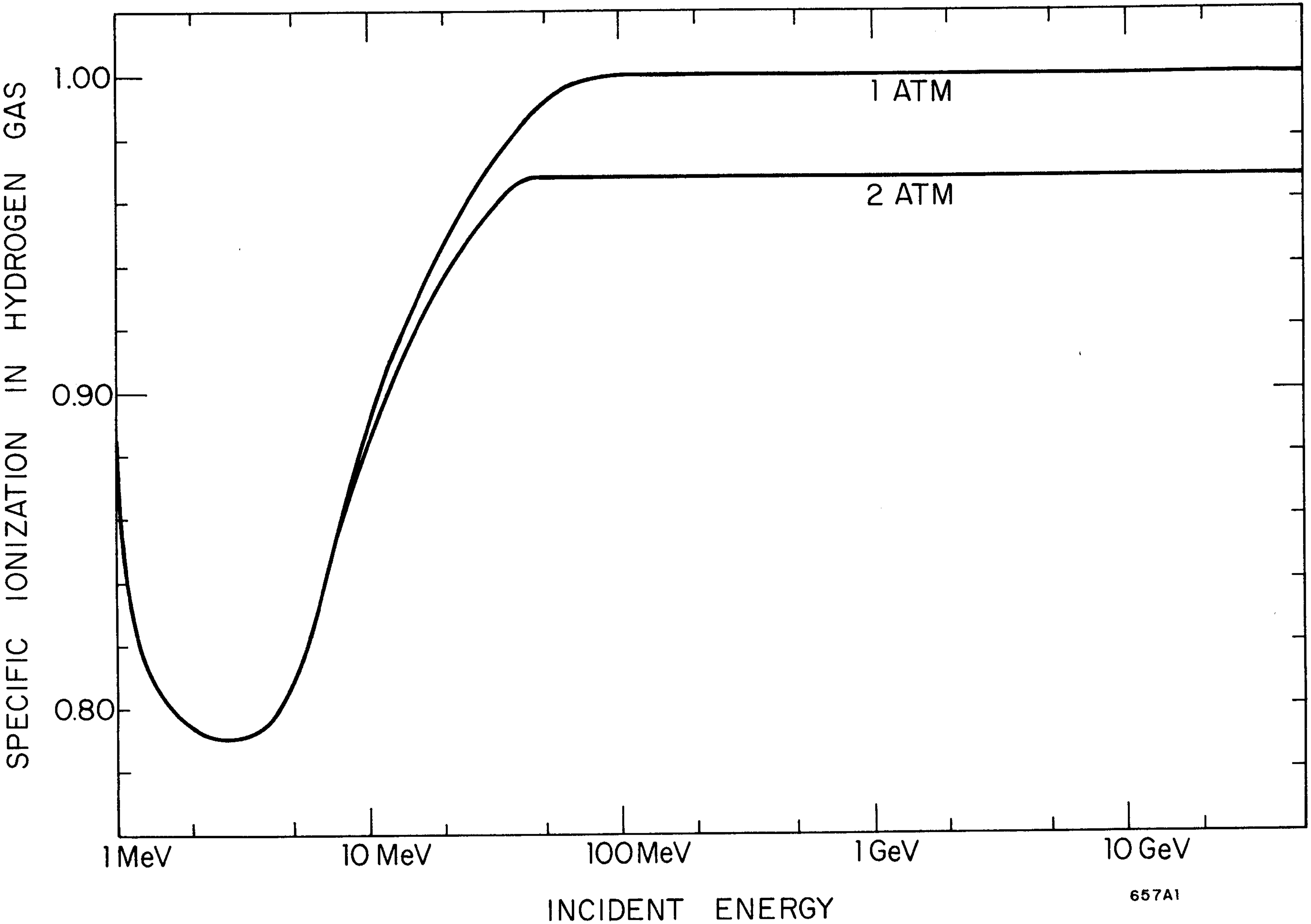
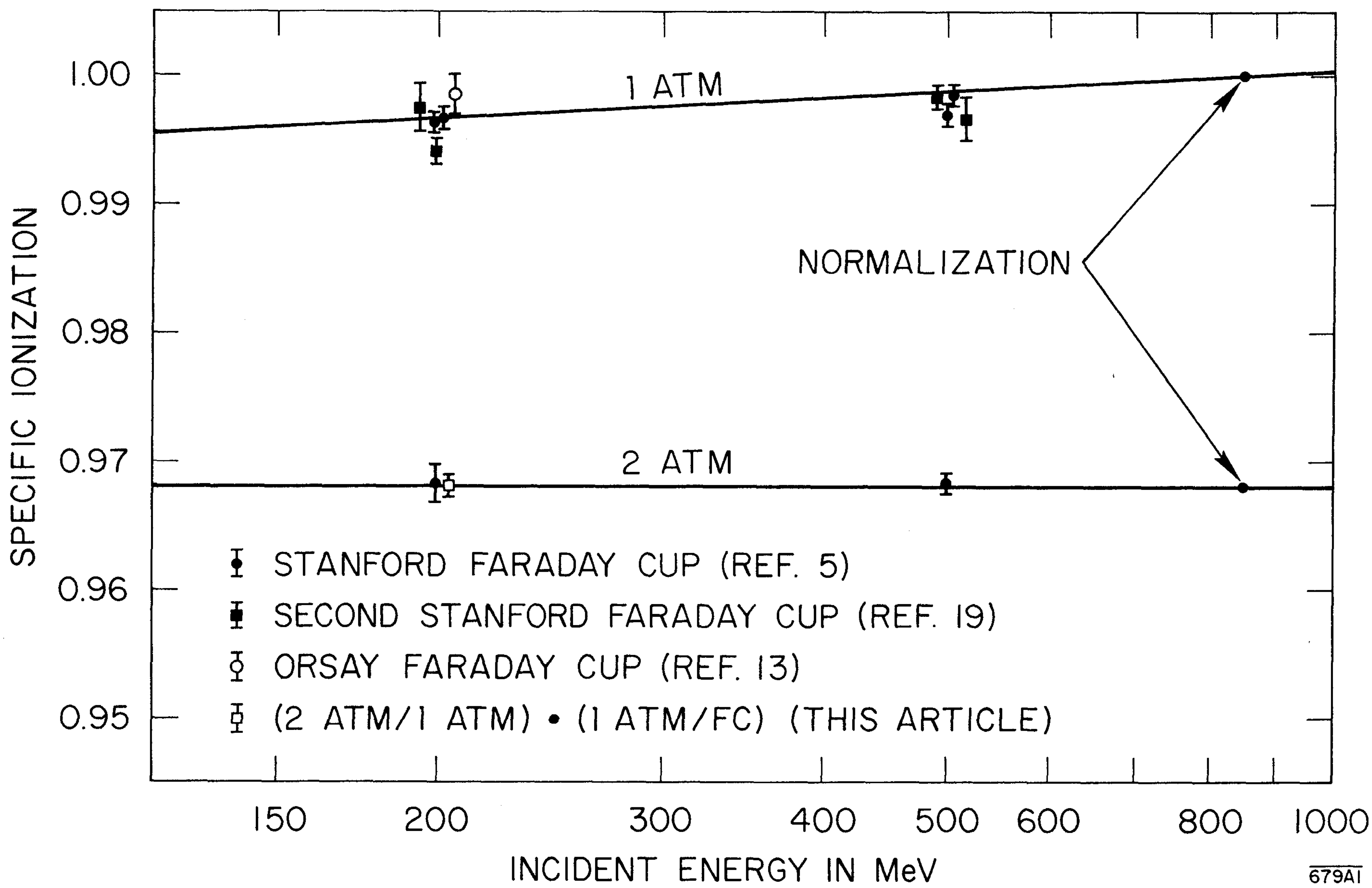

THIN FOILS OF
QUANTAMETER ION CHAMBER
BEAM
THIN WINDOW
POLYSTYRENE
INSULATORS
COPPER SCREEN
DEFINING RADIAL
GAPS FOR
COMPENSATION
COPPER
COLLECTOR PLATE
COPPER
HIGH VOLTAGE PLATE
657A9

Fig. 2



1.00
0.90
0.80
SPECIFIC IONIZATION IN HYDROGEN GAS
1 ATM
2 ATM
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
INCIDENT ENERGY
657A1

FIG. 3



1.00
0.99
0.98
0.97
0.96
0.95
SPECIFIC IONIZATION
1 ATM
2 ATM
NORMALIZATION
STANFORD FARADAY CUP (REF. 5)
SECOND STANFORD FARADAY CUP (REF. 19)
ORSAY FARADAY CUP (REF. 13)
(2 ATM/1 ATM) • (1 ATM/FC) (THIS ARTICLE)
150
200
300
400
500
600
800
1000
INCIDENT ENERGY IN MeV
679A1

FIG. 4

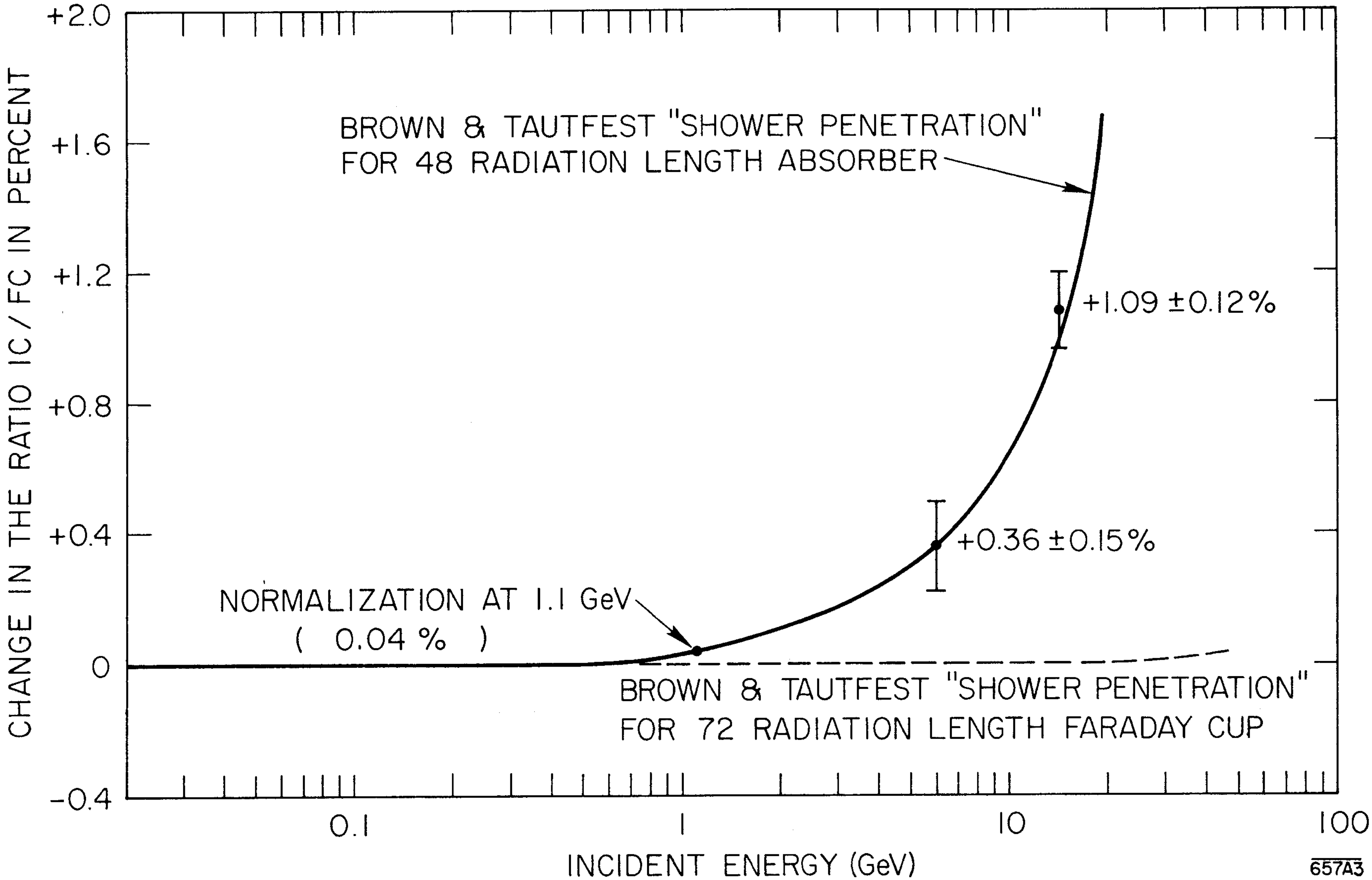

+2.0
+1.6
+1.2
+0.8
+0.4
0
−0.4
CHANGE IN THE RATIO IC / FC IN PERCENT
BROWN & TAUTFEST "SHOWER PENETRATION"
FOR 48 RADIATION LENGTH ABSORBER
+1.09 ±0.12%
+0.36 ±0.15%
NORMALIZATION AT 1.1 GeV
(0.04 %)
BROWN & TAUTFEST "SHOWER PENETRATION"
FOR 72 RADIATION LENGTH FARADAY CUP
0.1
1
10
100
INCIDENT ENERGY (GeV)
657A3

FIG. 5

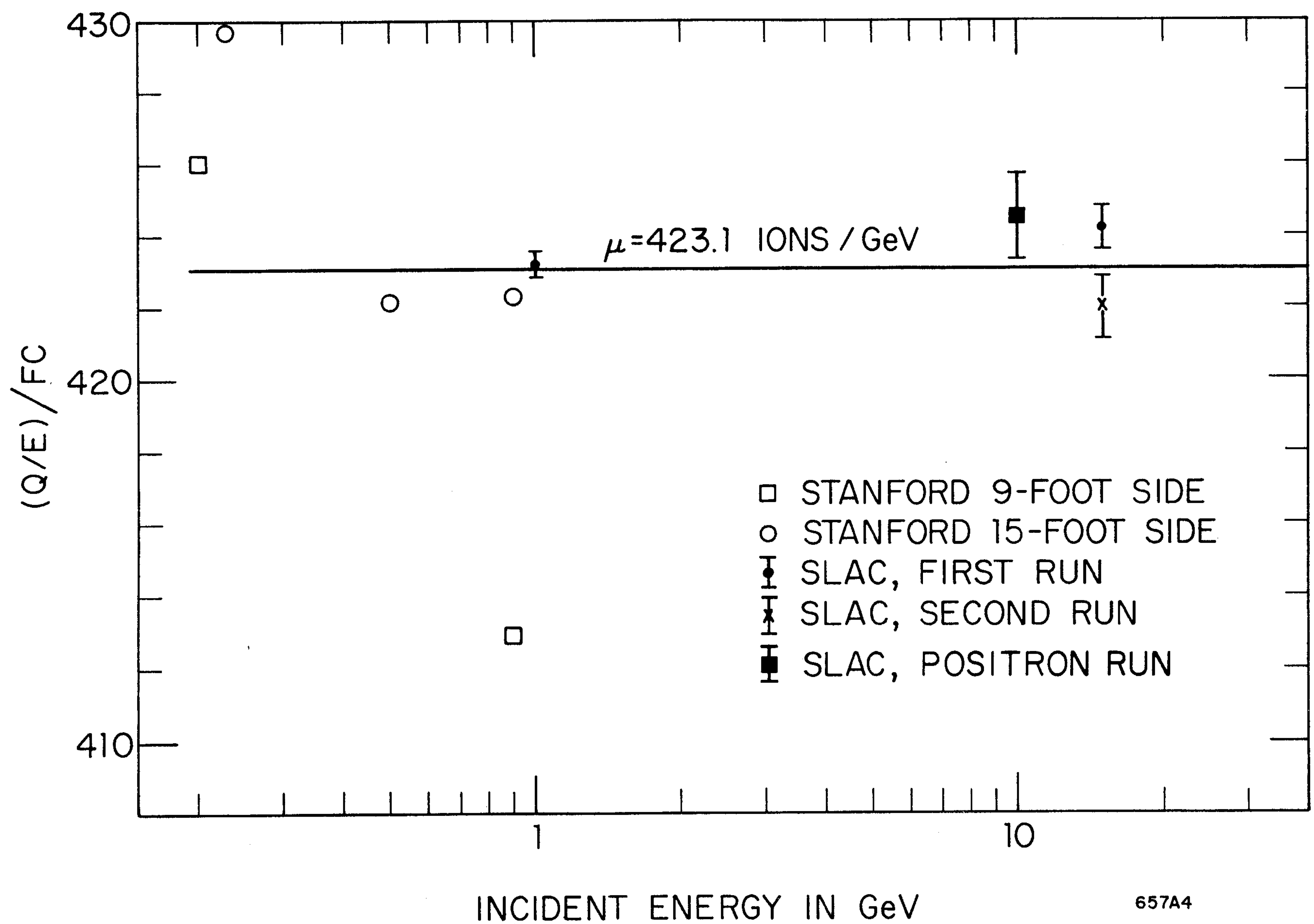
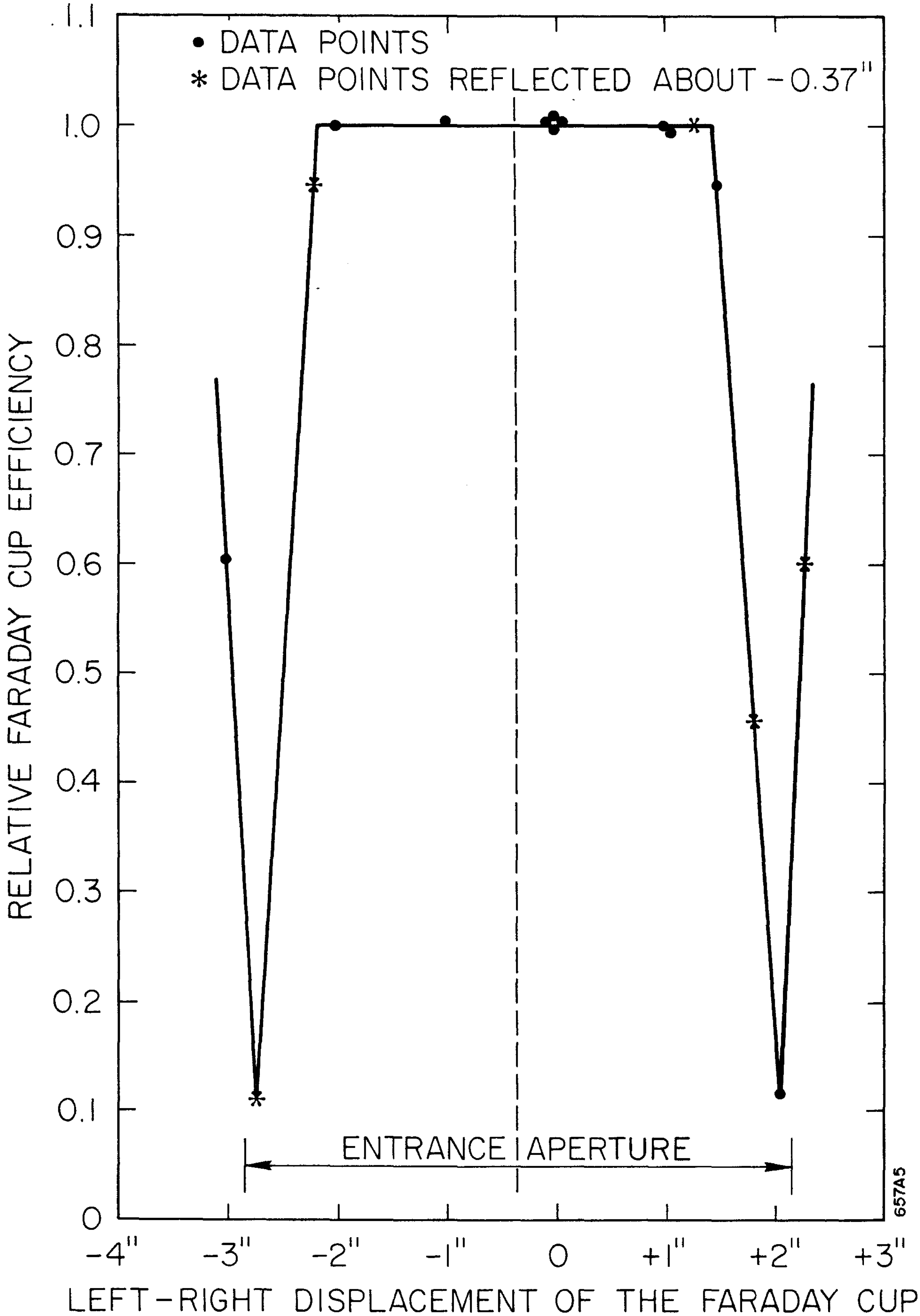
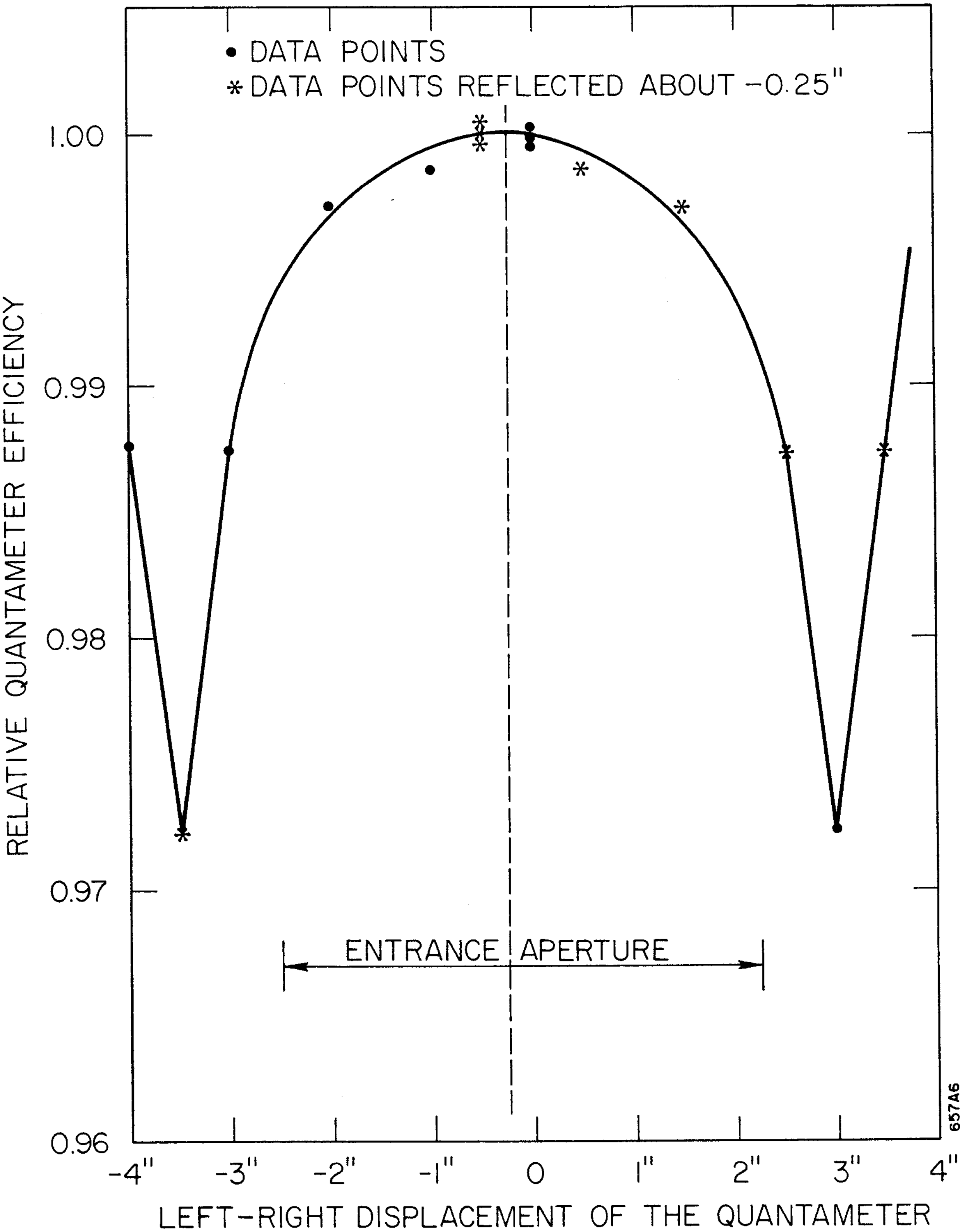

430
420
410
(Q/E)/FC
1
10
INCIDENT ENERGY IN GeV
μ=423.1 IONS / GeV
STANFORD 9-FOOT SIDE
STANFORD 15-FOOT SIDE
SLAC, FIRST RUN
SLAC, SECOND RUN
SLAC, POSITRON RUN
657A4

FIG. 6



• DATA POINTS
* DATA POINTS REFLECTED ABOUT -0.37"
RELATIVE FARADAY CUP EFFICIENCY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ENTRANCE APERTURE
657A5
-4"
-3"
-2"
-1"
0
+1"
+2"
+3"
LEFT-RIGHT DISPLACEMENT OF THE FARADAY CUP

FIG. 7



• DATA POINTS
* DATA POINTS REFLECTED ABOUT -0.25"
1.00
0.99
0.98
0.97
0.96
RELATIVE QUANTAMETER EFFICIENCY
ENTRANCE APERTURE
-4"
-3"
-2"
-1"
0
1"
2"
3"
4"
LEFT-RIGHT DISPLACEMENT OF THE QUANTAMETER
657A6

FIG. 8

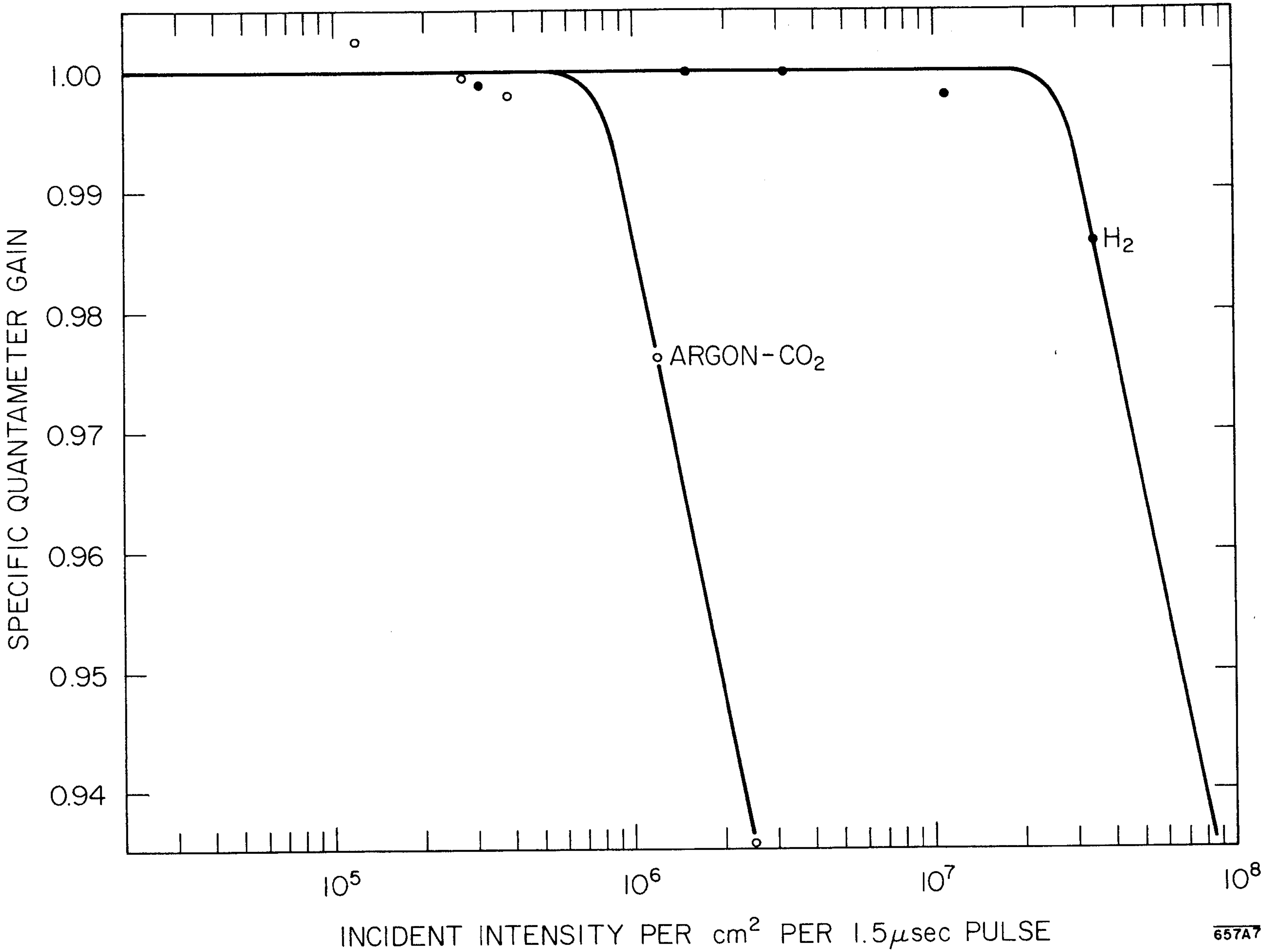

1.00
0.99
0.98
0.97
0.96
0.95
0.94
SPECIFIC QUANTAMETER GAIN
ARGON-CO_2
H_2
10^5
10^6
10^7
10^8
INCIDENT INTENSITY PER cm^2 PER $1.5 \mu sec$ PULSE
657A7

FIG. 9

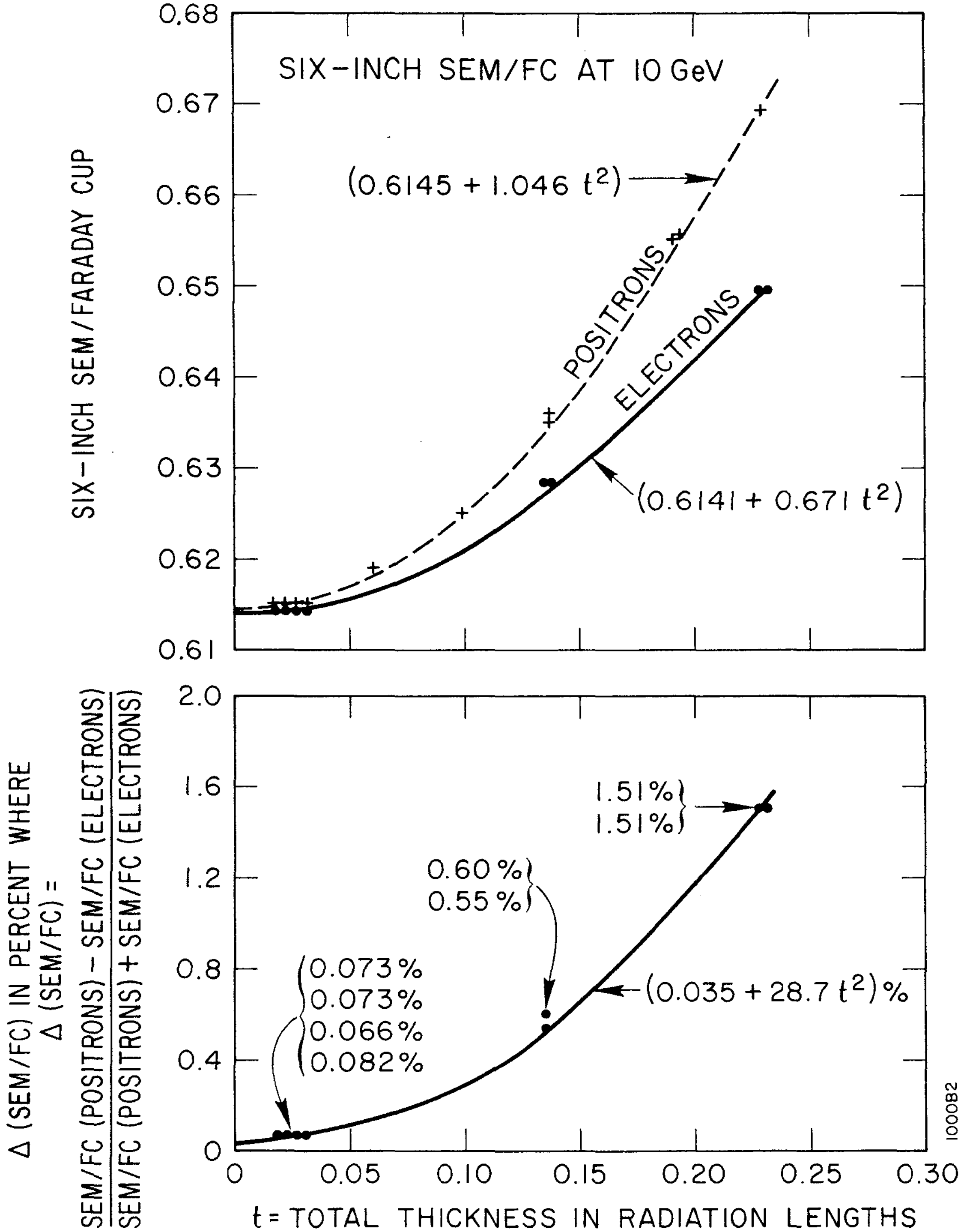

SIX-INCH SEM/FC AT 10 GeV
(0.6145 + 1.046 t²)
POSITRONS
ELECTRONS
(0.6141 + 0.671 t²)
SIX-INCH SEM/FARADAY CUP
0.61
0.62
0.63
0.64
0.65
0.66
0.67
0.68
1.51%
1.51%
0.60 %
0.55 %
0.073%
0.073%
0.066%
0.082%
(0.035 + 28.7 t²)%
Δ (SEM/FC) IN PERCENT WHERE
Δ (SEM/FC) =
SEM/FC (POSITRONS) − SEM/FC (ELECTRONS)
SEM/FC (POSITRONS) + SEM/FC (ELECTRONS)
0
0.4
0.8
1.2
1.6
2.0
0
0.05
0.10
0.15
0.20
0.25
0.30
t = TOTAL THICKNESS IN RADIATION LENGTHS
1000B2

Fig. 10

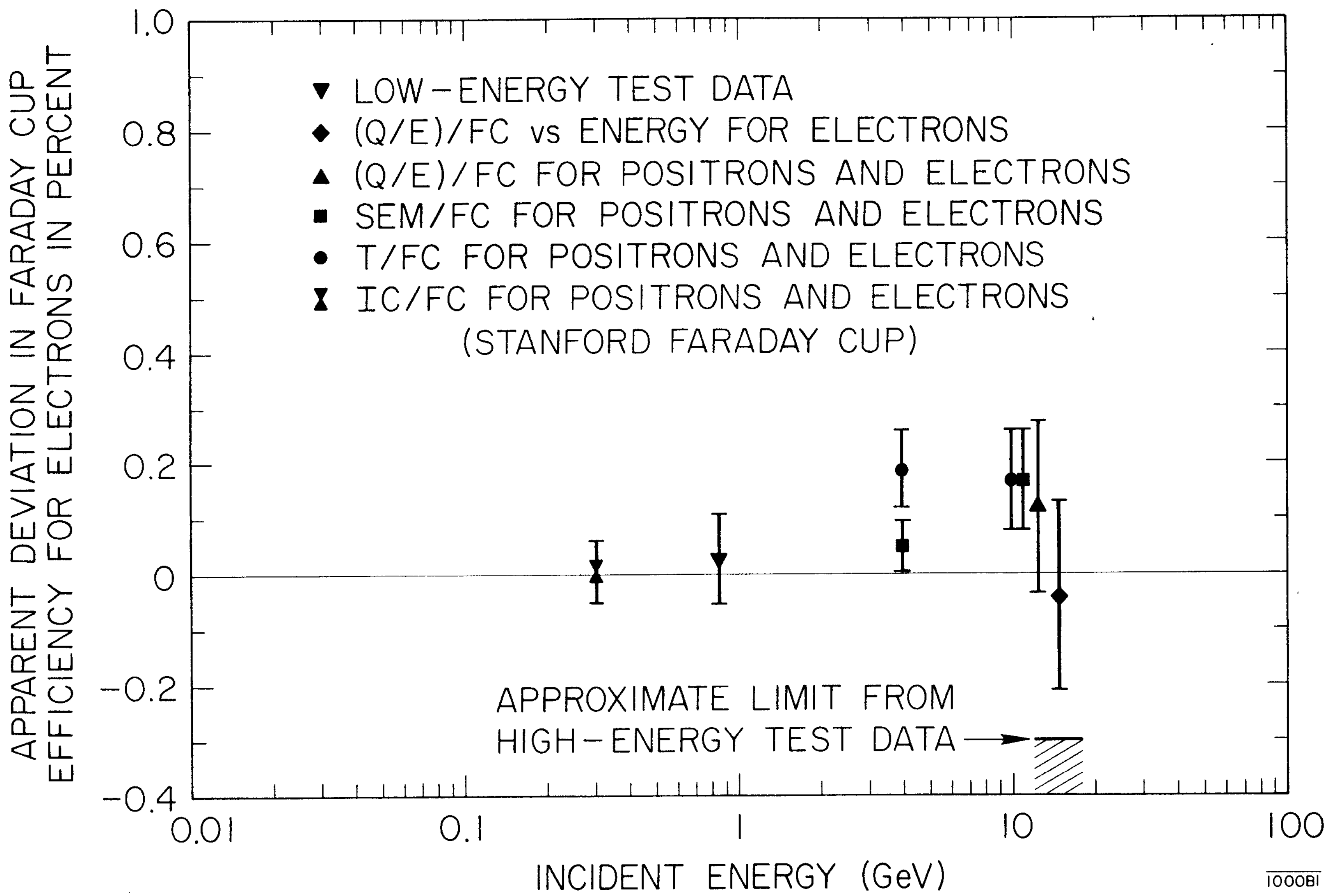

LOW-ENERGY TEST DATA
(Q/E)/FC vs ENERGY FOR ELECTRONS
(Q/E)/FC FOR POSITRONS AND ELECTRONS
SEM/FC FOR POSITRONS AND ELECTRONS
T/FC FOR POSITRONS AND ELECTRONS
IC/FC FOR POSITRONS AND ELECTRONS
(STANFORD FARADAY CUP)
APPROXIMATE LIMIT FROM
HIGH-ENERGY TEST DATA
APPARENT DEVIATION IN FARADAY CUP
EFFICIENCY FOR ELECTRONS IN PERCENT
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0.01
0.1
1
10
100
INCIDENT ENERGY (GeV)
1000B1

Fig. 11