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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 as well as for several hydrogen ion chambers used as reference monitors. 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. Tests carried out at energies up to 15 GeV indicate an absolute efficiency of (100.0 ± 0.2)%. The quantameter was designed to have a gain linear in electron, positron, or photon energy to ± 0.1%. In tests with the Faraday cup using the electron beams at Stanford and at SLAC, the quantameter has been calibrated to ± 0.3% and its linearity established to an accuracy of ± 0.2% at energies up to 15 GeV.

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I. INTRODUCTION

Faraday cups have for many years served as final absolute beam monitors at linear electron accelerators[1,2] and more recently at some electron synchrotrons.[3,4] The efficiency of a Faraday cup for electrons or for positrons[5] is expected a priori to be unity, and the various effects which can lead to departures from this value are quite small and subject to experimental verification on the 0.1% level.[5] Similarly, quantameters of the type designed by Wilson[6] have been widely used as photon monitors, primarily at electron synchrotrons[4,6,7,8,9] where intense external electron beams have only recently been developed. The gain of a quantameter, typically in the range 10^3 to 10^4 ions per GeV of incident photon, electron, or positron energy, is linear in energy and independent of intensity over a reasonable range; and it can be estimated a priori to an accuracy of a few percent. Within this accuracy, quantameters have frequently served as absolute monitors without calibration.

The design specifications for the Beam Switchyard and for the spectrometers at SLAC indicate that momenta[10] and angles will be measurable with such high precision that scattering and other experiments should be feasible with absolute errors of 1% or less. It is then fully appropriate that reliable absolute beam monitors be developed for SLAC which have efficiencies that are known to much better than 1%, as would be required by such experiments. While various design short cuts have been proposed and sometimes used in the case of Faraday cups,[2,3] we feel that these are not appropriate in a device which ultimately serves as a laboratory standard and which costs in the end less than the accelerator beam time needed to test it and far less than the additional apparatus in even one of the numerous experiments which it serves.

In the case of the quantameter, we have assumed from the beginning that it would be calibrated with the Faraday cup. This in no sense relaxes the requirements of energy linearity and of reproducibility; on the contrary, since the quantameter can be calibrated and thoroughly tested using the Faraday cup, it too becomes a precise beam monitor when linearity and reproducibility are achieved.

II. DESIGN PARAMETERS

A. Faraday Cup

In designing a Faraday cup for use at SLAC energies, we have followed rather closely the recipe given by Brown and Tautfest.[1] The result, shown in Fig. 1, is 72 radiation lengths along the beam line with a radius of 46 radiation lengths. Equation 8 of Ref. 1 then predicts a net loss of electrons due to shower penetration amounting to about 0.01% at 20 GeV and about twice that at 40 GeV. This equation is based upon the data of Kantz and Hofstadter[11] at 185 MeV and gives a larger prediction for the longitudinal and especially for the radial losses than more recent data and calculations at higher energies.[12] 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%.

We have chosen a highly re-entrant geometry for the cup-proper to minimize the losses due to backward-going shower electrons,[12] to backscattering of primaries, and to the emission of secondary electrons in the backward direction. There is some evidence[13] that the pseudo re-entrant geometry used in the Orsay cups[2] leads to a loss of electrons amounting to about 0.2% of the incident electron or positron intensity at 500 MeV. As described in Ref. 3, a pseudo re-entrant geometry was also adopted for the CEA cup, i.e., the flat front face was covered with an aluminum collector hood 1/2 inch thick having a 6-inch port for the beam to enter. However, prior to the tests reported in Ref. 9, a thick-walled re-entrant hole was constructed by adding to the front face a suitable hollow cylinder of lead. The DESY cup[4] is also highly re-entrant.

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. 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 copper core should also help to reduce backscattering. 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%; but the permanent magnets and carbon plug provide a simple means of insuring that these effects will be completely negligible.

Ionization of the residual atoms in the partial vacuum surrounding the cup-proper is not important for secondary particles which leave the cup since their number is small compared to the number of primaries incident. If we assume that all of the positive ions (or alternatively, all of the electrons) formed in the snout and in the hole by the incident beam are collected by the cup, we obtain an upper limit of $\pm$ 0.1% for this effect at a pressure of 10^{-4} torr. A more realistic assumption is that only the ions in the gap between the exit of the snout and the entrance of the hole are collected. This gives $\pm$ 0.01% at 10^{-4} torr.

The Vacion pump, which is connected to the vacuum chamber in such a way that ions from the pump cannot reach the cup, insures that the pressure will normally be well below this value. The ion gauge supplements the gauge in the pump and serves as a check on the actual pressure in the vacuum chamber. The ion gauge is not used during runs since electrons and ions from the gauge reach the cup in significant numbers.

As indicated in Fig. 1, 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. Normally the vacuum chamber is grounded in the experimental area while the guard is connected to the outer conductor of the coaxial signal cable and is independently grounded at the integrator.

In addition to facilitating independent grounding, the guard ring also permits the taking of "bias curves" in which the cup and guard float at a high voltage with respect to the vacuum chamber.[1] Such curves have frequently been used to place limits upon the efficiency of a Faraday cup and typically give values of order ± 1%, even for cups designed for much higher precision. This is due to a considerably enhanced collection efficiency for secondary electrons[14] emitted from the entrance window when the cup is biased positively and to a similar enhancement of the loss due to backward going secondaries when the bias is negative. Such curves are not useful on the level of ± 0.1%, and one must isolate the spurious effects and carry out specific tests for each.[5]

The SLAC cup is equipped with a copper core 10 inches in diameter and 10 inches long, this being about twice the length to shower maximum in copper at

20 GeV. 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. These features permit a factor of 10 increase in the long term power rating and a factor of 100 increase in the short term rating as compared with the corresponding cup having a lead core and reflecting aluminum or steel walls. During long integrations at 10 kW, the lead outside the copper core may begin to melt; while at a level of 100 kW, it should be possible to melt the copper near shower maximum along the beam line. Since the lead is incased in iron, except for the copper lining of the hole, and since the insulators are ceramic, it is not clear to what extent high power levels will permanently damage the cup. In any case, we hope to restrict the long term and short term power levels to 1 kW and 10 kW, respectively. This is well below the 600 kW[15] rating of the SLAC electron beam at full power; but it is sufficient to permit tests and calibrations of the high intensity SLAC toroids[16] over a significant intensity and energy range.

We may summarize the Faraday cup design by noting that the "front end" is similar to, but somewhat more conservative than, the front end of the Stanford cup whose efficiency was believed, on the basis of experimental tests,[5] to be $(100.00 \pm 0.15)\%$ at energies from 200 to 850 MeV. The concessions made to the higher power and higher energy levels at SLAC should in no way affect the efficiency at beam energies below about 1 GeV. Thus, while other tests are desirable and were carried out, a sufficient test is to show that the efficiency of the SLAC cup is independent of energy in the range from 1 to 20 GeV.

B. Quantameter

The 20-GeV quantameter is shown in Fig. 2. Conceptually the design follows closely the one adopted originally by Wilson,[6] 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 the 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." (Assuming an attenuation length for low energy gammas in copper of 4.0 cm, we require a compensating gap equivalent to 4 plates and thus to 4 average gaps in the quantameter.)

For convenience, we have added a thin plate (less than 10^{-3} radiation lengths) ion chamber in front of the quantameter. Once the ion chamber and quantameter have been calibrated, the ratio of quantameter to ion chamber gains is a direct measure of the electron or positron beam energy. Furthermore, since the two monitors share the same gas, the ratio of their gains at a given energy should be highly reproducible.

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. Using the data of Wilson with the corrections noted in Ref. 7, we have calculated a "quantameter constant" of $(1.440 \pm 0.010) \times 10^{18}$ 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 radial energy losses due to shower penetration are only of order 0.1% at 20 GeV.[12] 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[12] and 1.8 to 2.4% of the energy at 20 GeV. The linearity without compensation would thus be of order 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%.

In order to obtain high reproducibility as well as low recombination rates, we have chosen initially to flow pure hydrogen through the quantameter at ambient temperature and pressure. Under these circumstances, the composition of the gas does not change with time, as it may with argon-CO_2[8,17]; 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[14] 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.

In summary, the quantameter is expected to be linear in energy and reproducible to an accuracy of 0.1 to 0.2%. Since the energy of the electron or positron beam is expected to be determined absolutely to an accuracy of ± 0.2%,[10] a precise test of the quantameter is possible. In particular, the ratio: (quantameter gain/energy)/(Faraday cup efficiency) = (Q/E)/FC should be independent of the beam energy to a few tenths of one percent.

C. Ion Chambers

The hydrogen ion chambers are similar to those which have been used for many years, particularly in positron scattering experiments.[5,13] An example of such a chamber is shown in Fig. 3. The basic unit consists of a "collector plate" centered between two "high voltage plates" and isolated electrically from these plates by means of grounded "guard rings." In the chambers described here, the plates are made of 0.0002-inch aluminum foil glued to polystyrene rings previously cooled below 0° C in a deep freeze. The subsequent expansion of the rings produces wrinkle-free surfaces of mirror flatness. Rings of different thicknesses are chosen depending upon the gain and gas recombination characteristics required.

A beam position indicator or "beam sniffer" is constructed[5] by using collector plates which are split diagonally into two halves after gluing. One pair of split collectors is used for right-left centering of the beam and another pair, rotated 90°, for up-down centering. The two pairs of split collectors are arranged back to back, separated by 0.001-inch mylar insulation. Thus they replace the single collector plate of a standard ion chamber.

A "beam halo monitor" is constructed by cutting a concentric hole in a collector plate after the foil has been glued to its supporting ring. Two of these annular collector plates are installed back to back on either side of a grounded plate which collects the ions formed at radii smaller than the hole in each collector. The annular collectors are insulated from the grounded center plate by 0.001-inch mylar which has the same annular shape as the collector in order to allow ions to reach the grounded plate. Thus a single collector is replaced in the beam halo monitor by an annular aluminum collector, an annular mylar insulator, a grounded center plate, a second annular mylar insulator, and a second annular aluminum collector. This is the first time we have constructed a beam halo monitor, and it was not clear a priori to what extent photo-ionization and the radial migration of ions and electrons would simulate a finite radial distribution of particles in the beam.

The "beam ion chamber" contains a beam sniffer and two ion chambers of 0.4 and 1.0 inch thickness. The sensitive diameter is 5 inches. The "spectrometer ion chamber" consists of a beam sniffer and three ion chambers of respectively 0.4, 1.0, and 2.0 inch thickness. The sensitive diameter of the plates is 10 inches. The "beam halo monitor" consists of a beam sniffer, an ion chamber 0.4 inch thick, and six annular collectors with inside diameters of 0.5, 1.0, 2.0, 3.0, 4.0, and 6.0 inches. The sensitive outside diameter of the plates in the beam halo monitor is also 10 inches. In each case, the compartments for the sniffer and for the beam halo monitor collectors are 0.5 inch thick.

A special "high gain ion chamber" consists of a series of 10 ion chambers, each 4 inches thick, with the collector plates internally connected in parallel. (The separation from collector to high voltage plates is 2 inches with the guard rings located 0.1 inch from the collectors.) When filled with the standard argon-CO_2 mixture at 2 atm absolute pressure, the gain of this device is of order 2×10^4 ions per incident beam particle. This permits the accurate monitoring of secondary beams having intensities of as few as 10 particles per pulse, 60 pulses per second. (The dark current due to cosmic rays is expected to be equivalent to about 1 μ meson per pulse.)

The beam and spectrometer ion chambers and the beam halo monitor are about 0.001 radiation length thick when 0.001-inch mylar windows are used and are about 0.002 radiation lengths when 0.002-inch aluminum is used instead. The thin windows, which have a diameter of 2 inches, are epoxied onto 0.010-inch aluminum end plates. These windows are capable of supporting a 1-atm pressure differential; yet they have a small thickness for the direct beam and do not require heavy supporting flanges of small diameter. The high gain ion chamber has a thickness of about 0.03 radiation length, most of which is due to the gas.

Hydrogen ion chambers are particularly well suited as non-beam-destructive reference monitors in the testing of Faraday cups and quantameters. The high gain permits tests of the quantameter at low intensities where toroids[16] and secondary emission monitors[14] 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. A further advantage of particular interest to us here is illustrated in Fig. 4, where we have plotted theoretical[18] 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.

Now 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: (ion chamber gain)/(Faraday cup efficiency) = IC/FC either increases with energy at high energies or is constant. Previous measurements of this ratio[5,13] in the range from 200 to 850 MeV have indicated that the ionization is already constant to 0.1% at 200 MeV with 2 atm and that it is within a few tenths of 1% of being constant for 1 atm. One expects, therefore, that at 2 atm the ratio of IC/FC for the SLAC Faraday cup will be constant to 0.1% over the full energy range from 200 MeV to 20 GeV.

D. Integrators

Two types of "slideback" current integrators were used interchangeably in the beam monitor tests described below. 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. We should mention, for example, that the monitor tests reported here depend always 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. 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. With good cables, the leakage currents are normally less than 10^{-13} A.

While in practice the response of a monitoring system depends upon the integrator used, the tests of the intrinsic Faraday cup efficiency depend only upon the linearity and reproducibility of the integrators and not upon the absolute calibration. Similarly, the quantameter gain is determined by means of ratio measurements in which the value of the capacitor chosen for the ion chamber reference monitor cancels out and in which the relative values of the capacitors used with the Faraday cup and the quantameter are determined by discharging a single reference capacitor successively into each of the monitor capacitors. The nonlinearity of the integrators and the uncertainties in the relative capacitor values are somewhat less than ±0.1%.

Finally, 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.

III. TEST DATA

A. Faraday Cup Vacuum

The effect of an imperfect vacuum in the Faraday cup was tested with electrons at 200 MeV by comparing 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 the estimate of Section IIA, and it should be independent of energy. The collection efficiency for the ions probably depends upon the voltage difference between the cup-proper and the vacuum chamber; but this difference is in the millivolt range while the electrons from ionization typically have energies of the order of electron volts. This suggests that the change in Faraday cup efficiency due to ionization may to some extent be reproducible and that this experimental test has some generality, at least as an indication of the order of magnitude involved. The pressure was less than 0.5×10^{-4} torr for the tests which follow.

B. Secondary Emission

Secondary emission from the entrance window of the Stanford Faraday cup was investigated in Ref. 5 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 the 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 $\left(+0.05 \begin{smallmatrix} + 0.06 \\ - 0.05 \end{smallmatrix}\right)\%$. The error was calculated from the variations in a number of repeated measurements and takes into account the intrinsic sign of effect being tested. The change due to backward going secondaries was $\left(-0.02 \begin{smallmatrix} + 0.02 \\ - 0.06 \end{smallmatrix}\right)\%$. The net result of the low energy effects including ionization was $\left(+0.03 \begin{smallmatrix} + 0.08 \\ - 0.08 \end{smallmatrix}\right)\%$.

As already noted, the "front-end" of the SLAC Faraday cup is quite similar to that of the Stanford cup. The geometry is, however, somewhat more reentrant, the snout somewhat longer, and the magnets rather stronger. The secondary emission data for the Stanford cup thus provide a reliable upper limit on the effect of secondary emission for the SLAC cup.

C. Comparison of the SLAC and Stanford Faraday Cups

As a check of the SLAC and Stanford Faraday cups below 1 GeV, we have compared the two 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[5]. The relative efficiencies observed with a 1-cm diameter beam spot were

$$(FC_{NEW} - FC_{SLAC})/FC_{SLAC} = (-0.08 \pm 0.10)\% ,$$

$$(FC_{OLD} - FC_{SLAC})/FC_{SLAC} = (-0.31 \pm 0.09)\% ,$$

$$(FC_{OLD} - FC_{NEW})/FC_{NEW} = (-0.23 \pm 0.12)\% .$$

As usual, the errors have been calculated from the variations in a number of repeated measurements. While the $(-0.31 \pm 0.09)\%$ 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 $(100.03 \pm 0.08)\%$, the result indicated by the low energy tests of Section IIIB.

D. Ion Chamber versus Faraday Cup

The data from Stanford[5] and Orsay[13] on the "energy dependence of the ionization of hydrogen gas" are summarized in Fig. 5, along with unpublished measurements made at Stanford[19] with a second Stanford Faraday cup of a different design.[20] In each case, the data at 1 atm have been normalized to unity at 850 MeV, while the data from Ref. 5 at 2 atm have been normalized to 0.968

at the same energy. These values were taken from Fig. 4; 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 $(+0.37 \pm 0.05)\%$. The result at 2 atm from Ref. 5 is $(-0.03 \pm 0.11)\%$. In addition, we have recently compared the energy dependence at 2 atm with that at 1 atm obtaining a change in the ratio IC(2 atm)/IC(1 atm) of $(-0.38 \pm 0.04)\%$ over the range from 200 to 900 MeV. This, together with the 1 atm data, yields an independent measurement of $(-0.01 \pm 0.07)\%$ for the energy dependence at 2 atm, in excellent agreement with the 2 atm data from Ref. 5. The theoretical curves shown in Fig. 4 and based on Ref. 18 agree qualitatively with experiment but predict a somewhat lower energy for the termination of the relativistic rise at 1 atm.

The experimental setup used in the first run at SLAC is shown in Fig. 6. The results obtained for the ratio IC(2 atm)/FC using the SLAC Faraday cup are shown in Fig. 7. These data indicate an increase of $(1.09 \pm 0.12)\%$ 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 at less than 1 GeV.

The most promising explanation for the energy dependence of the ratio IC(2 atm)/FC seemed to be a background of low energy, shower penetration gamma rays from the 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. The bend following the 30 radiation length momentum slits is only 12° for the "A Beam" at SLAC as compared with a bend of 30° at Stanford and a double 30° bend following the slits for the 1 GeV station at Orsay. The high energy of the SLAC beam gave further support to this hypothesis, while the data fit surprisingly well a "shower penetration" energy dependence (as distinguished from a relativistic rise). This is indicated by the solid curve in Fig. 7, which is based on Eq. 8 of Ref. 1 for an absorber thickness of 48 radiation lengths of lead. The bending magnets, the vacuum chamber following the slits, and the small thickness of material in the beam seemed to preclude the possibility of a significant contamination of low energy positrons and electrons.

In a second attempt, the "spectrometer ion chamber" and "beam halo monitor" were moved 2 m farther upstream of the Faraday cup-quantameter support stand, while the "beam ion chamber" was mounted on axis in back of the Faraday cup. This reduced the material in the beam in front of the ion chambers (mostly air) from about 0.011 radiation length to about 0.003 radiation length and would have decreased the energy dependence significantly had it depended upon this parameter. The same conclusion applies if the effect was due to ionization by radiation traveling backward from the cup. On the other hand, if the cause was a general background of low energy gammas leaving the Beam Switchyard, then a slight enhancement should be observed, depending upon the distance to the source. The ion chamber mounted in back of the Faraday cup provided a sensitive test for shower penetration, for penetrating μ's in the incident beam, and for μ pairs produced in the cup.

The energy dependence observed on the second run was $(1.36 \pm 0.20)\%$ for 1 atm and $(1.61 \pm 0.25)\%$ for 2 atm. It is important to note that the two ion chambers used in this test had the same diameter (and the same volume per unit thickness along the beam) as the 2 atm chamber used on the first run. Thus they had roughly the same efficiency for a diffuse background originating in the Beam Switchyard. The result indicates a small enhancement of the effect, as would be expected from such a source located many meters upstream from the ion chambers. The relativistic rise at 1 atm as compared with 2 atm is $(+\ 0.25 \pm 0.33)\%$. This is consistent with zero relativistic rise for both 1 and 2 atm and is in agreement with the low energy data and with the theory.

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 contribute only 0.03% to the ratio of IC/FC in the geometry of the first run. The result can also be used to infer an upper limit on the charge leaving the copper core of the Faraday cup. 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 backscattered primaries (i.e., to electrons only). The permanent magnets will, of course, further reduce any loss of charged particles. If the ionization is due to a mixture of electrons, positrons, and gammas from the shower, as seems more probable, the change in Faraday cup efficiency would be much smaller than 0.1%. Thus, while the quantameter ion chamber did not provide precise normalization for the quantameter as originally intended, it did contribute useful information.

Assuming all μ mesons were within the 5-inch diameter sensitive volume of the ion chamber in back of the Faraday cup, we can set an experimental upper limit of 0.1% upon the total number of penetrating μ mesons arriving with the incident beam or produced in the cup at 15 GeV. A limit of 0.001% can be set on the change in Faraday cup efficiency due to μ pairs which eject electrons as they leave the cup. Assuming that equal numbers of pairs and Compton electrons leave the cup due to shower penetration, and taking into account the area of the back of the cup and the distribution of particles in the penetrating component of the shower, we obtain a limit of 0.2% for the shower penetration at 15 GeV. Again, if the penetrating gammas (which greatly outnumber the electrons and positrons) produce a significant fraction of the ionization, then a much smaller limit results. The quantameter and quantameter ion chamber showed no measurable radiation when the Faraday cup was in the beam. This places a limit of less than 0.1% for the radial shower penetration from the Faraday cup.

The data above indicate that both the relativistic rise in ionization and the shower penetration of the Faraday cup are far too small to explain the energy dependence observed in the ratio of IC/FC. They are, in fact, consistent with zero. In a specific test for a diffuse beam contamination of low energy gammas, we looked at the outputs of the annular collectors of the beam halo monitor. These indicated that about 3% of the ions collected were outside a 6-inch diameter circle centered at the beam, rather more than were needed to explain the 1.09% energy dependence in IC/FC. This difference was explained by a subsequent test in the presumably halo-free beam at Stanford when a "halo" of about the same magnitude was again observed. Apparently this is due to photo-ionization or to the migration of ions and free electrons, effects which could presumably be reduced by inserting opaque cylindrical partitions between the high voltage and collector plates in such a way as to isolate the different collecting regions.

A conclusive test for low energy gammas 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 believe, therefore, that the energy dependence of Fig. 7 for IC(2 atm)/FC is spurious and due to a flux of low energy gammas from shower penetration. If the ion chamber efficiency is of order 1% for these gammas, the number of gammas is comparable with the number of primary electrons in the beam.

E. Quantameter versus Faraday Cup

Using the ion chambers as reference monitors which are, at least, stable at a given incident energy, we have measured the energy dependence of the quantity (quantameter gain/energy)/(Faraday cup efficiency) = (Q/E)/FC. 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 not sensitive to neutrals, and the quantameter is insensitive to gamma radiation having only about 0.6 MeV/15 GeV $\sim$ 0.004% of the energy of the incident beam and having an intensity comparable with the primary beam intensity.

The results at 1.0092 and 15.000 GeV are plotted in Fig. 8 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"

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

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 better than 1% at the time of these tests. 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 at 15 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 is (+0.07 ± 0.15)%, while the mean "quantameter gain" measured at SLAC is (423.1 ± 0.3) ions per GeV. The average of the Stanford measurements is (422.6 ± 2.8), which differs from the value at SLAC by (+0.12 ± 0.66)%.

In testing the energy dependence, we have used the "random errors" calculated from the variations in repeated measurements of the ratios observed at each energy, a procedure which is intended to expose systematic effects which are outside of these errors. As far as the SLAC data are concerned, there is no indication of such effects in the ratio (Q/E)FC, and it is reasonable to use the random errors as an indication both of the energy linearity of the quantameter and of any change in the efficiency of the Faraday cup. In assigning an absolute value for the quantameter gain, however, one should take into account systematic uncertainties, particularly those in the Faraday cup efficiency and in the incident energy.

Combining the measured energy dependence with the sum of the low energy effects from Section IIIA, we obtain a Faraday cup efficiency of 100.00% - (0.07 ± 0.15)% + (0.03 ± 0.08)% = (99.96 ± 0.17)% $\simeq$ (100.0 ± 0.2)% in the range from 200 MeV to 15 GeV. Assuming an absolute uncertainty of ± 0.2% in the energy determination at SLAC and combining this with the experimental uncertainty in the Faraday cup efficiency as well as with the small uncertainties in absolute temperature and pressure and in the relative values of the integrator capacitors, we arrive at an error estimate of $\pm$ 0.3% for the quantameter calibration. The gain is then (423.1 $\pm$ 1.2) ions per GeV for hydrogen at 30.00 inches Hg and 300° K over the energy range from 1 to 15 GeV. The gain with the standard 95% argon-5% CO_2 mixture is (4185 $\pm$ 12) ions per GeV measured at 16 GeV and corrected to the same temperature and pressure. The latter corresponds to an experimental "quantameter constant" at 800 mm Hg and 20° C of $(1.389 \pm 0.004) \times 10^{18}$ MeV/coulomb. This is 3.6 $\pm$ 0.8% lower than the predicted value of $(1.440 \pm 0.010) \times 10^{18}$ MeV/coulomb. Intercalibrations[7] of the Cornell and the Caltech quantameters with the Stanford Faraday cup yielded experimental values that were 3-4% low with experimental errors of $\pm$ 1.6%. The comparison[9] of the CEA quantameter and Faraday cup gave a quantameter constant that was low by (6 $\pm$ 1.5)%, while DESY[4] obtained a value 3.1% low with about the same errors. The difference in experimental and theoretical quantameter constants for the SLAC quantameter with the argon-CO_2 filling is thus in good agreement with the results obtained elsewhere.

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. 9 for a beam spot of 1-inch diameter. The data indicate that for a point spot the efficiency is independent of position to $\pm$ 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. 10, 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. 11 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 the 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 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.

IV. DISCUSSION

We may summarize the results of this article as follows: We have constructed a 20-GeV Faraday cup and quantameter as well as several ion chambers used as reference monitors. The Faraday cup has been designed to have unity gain for electrons or positrons to an accuracy of better than $\pm$ 0.1% at energies up to 20 GeV. Tests carried out at energies from 200 MeV to 15 GeV indicate an absolute efficiency of (100.0 ± 0.2)% over this range. The quantameter was designed to have a gain linear in electron, positron, or photon energy to ± 0.1%. In tests with the Faraday cup using the electron beam at SLAC, the quantameter has been calibrated to ± 0.3% and its linearity established to an accuracy of ± 0.2% in the energy range from 1 to 15 GeV. The measured quantameter gain for hydrogen at 30.00 inches Hg and 300° K is (423.1 ± 1.2) ion pairs per GeV. The quantameter constant with 95% argon-5% CO_2 is $(1.389 \pm 0.004) \times 10^{18}$ MeV/coulomb. This is 3.6% less than predicted and is, therefore, similar to the results obtained elsewhere with other quantameters. The calibrations of the SLAC quantameter made at Stanford in the energy range from 200 to 900 MeV are generally consistent with the SLAC results, but suffer from relatively large uncertainties in the incident beam energy.

The data comparing the ion chambers and various Faraday cups at 200 and at 850 MeV indicate a relativistic rise in hydrogen at 2 atm of (-0.03 ± 0.11)% in this region. This seems to imply that the rise is of order 0.1% or less at all energies above 200 MeV. Because of a beam contamination of low energy gammas, however, we were able only to place an upper limit of (1.09 ± 0.12)% on the rise in the range from 1 to 15 GeV. We hesitate to give an absolute value for the specific ionization of hydrogen gas since our measurements seem to depend significantly upon the size and separation of the ion chamber plates. We note for the record, however, that the value for the ion chambers described here is in the neighborhood of 24.5 ion pairs per inch per incident electron at 300° K and 30.00 inches Hg.

The beam monitor tests also provide useful information on the performance of the new accelerator. The energy dependence studies indicate that the energy defined by the A Beam Switchyard is linear to $\pm 0.2\%$ in the range from 1 to 15 GeV. The quantameter gain measured at Stanford agrees with the SLAC result to $(+0.12 \pm 0.66)\%$, while the quantameter constant agrees with the values measured at other laboratories within typical errors of about $\pm 1.5\%$. These values indicate that the absolute energy at SLAC is probably correct to better than $\pm 1\%$. There is, in fact, no evidence that the energy of the electron beam is uncertain absolutely by more than $\pm 0.2\%$, the design value quoted in the SLAC USERS HANDBOOK.

ACKNOWLEDGEMENTS

A number of people have contributed to this program. Dr. D. Drickey participated in the runs both at Stanford and at SLAC and contributed many useful discussions. Dr. C. Buchanan was co-designer of the quantameter; Dr. J. Litt and Dr. D. Coward participated in the design of the beam halo monitor; and F. Martin was co-designer of the high gain ion chamber. The mechanical design of the Faraday cup, the quantameter, and their supporting stands was done by D. Danielson, who also supervised their construction and assembly. The electrical design and assembly of the remote control units and of certain of the electronic current monitors was done by M. Schlesinger, who also took part in the runs. A. Koula and G. Schultz did most of the construction and assembly. 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. The high level of performance achieved by the new accelerator in these early runs is remarkable in itself and would seem to herald future success for the laboratory!

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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.

3. Schematic diagram of the "beam ion chamber." The "spectrometer ion chamber," the "beam halo monitor," and the "high gain ion chamber" described in the text are similar in design but have different dimensions, depending upon the applications intended.

4. Specific ionization in hydrogen versus energy. The theoretical curves for 1 and 2 atm were obtained from Eq. 31 of Ref. 18 and were normalized to give a value of 1.00 for 1 atm at 10 GeV.

5. Specific ionization in hydrogen versus energy. The normalized experimental data at 1 and 2 atm from Refs. 5, 13, and 19 are shown as well as recent data comparing the ionization at 1 and 2 atm without a Faraday cup. The normalization from Fig. 4 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.

6. Plan view of the experimental setup for the first SLAC run. The Faraday cup and quantameter are controlled remotely and can be moved continuously through the beam as required in radial studies of monitor efficiency. For the second run, the "beam halo monitor" and the "spectrometer ion chamber" were moved 2 m upstream, while the "beam ion chamber" was mounted behind the Faraday cup to investigate penetration.

7. 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. 1 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 by shower penetration gamma rays of about 1 MeV which accompany the momentum analyzed primary beam.

8. 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%.

9. 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.

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

11. 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.

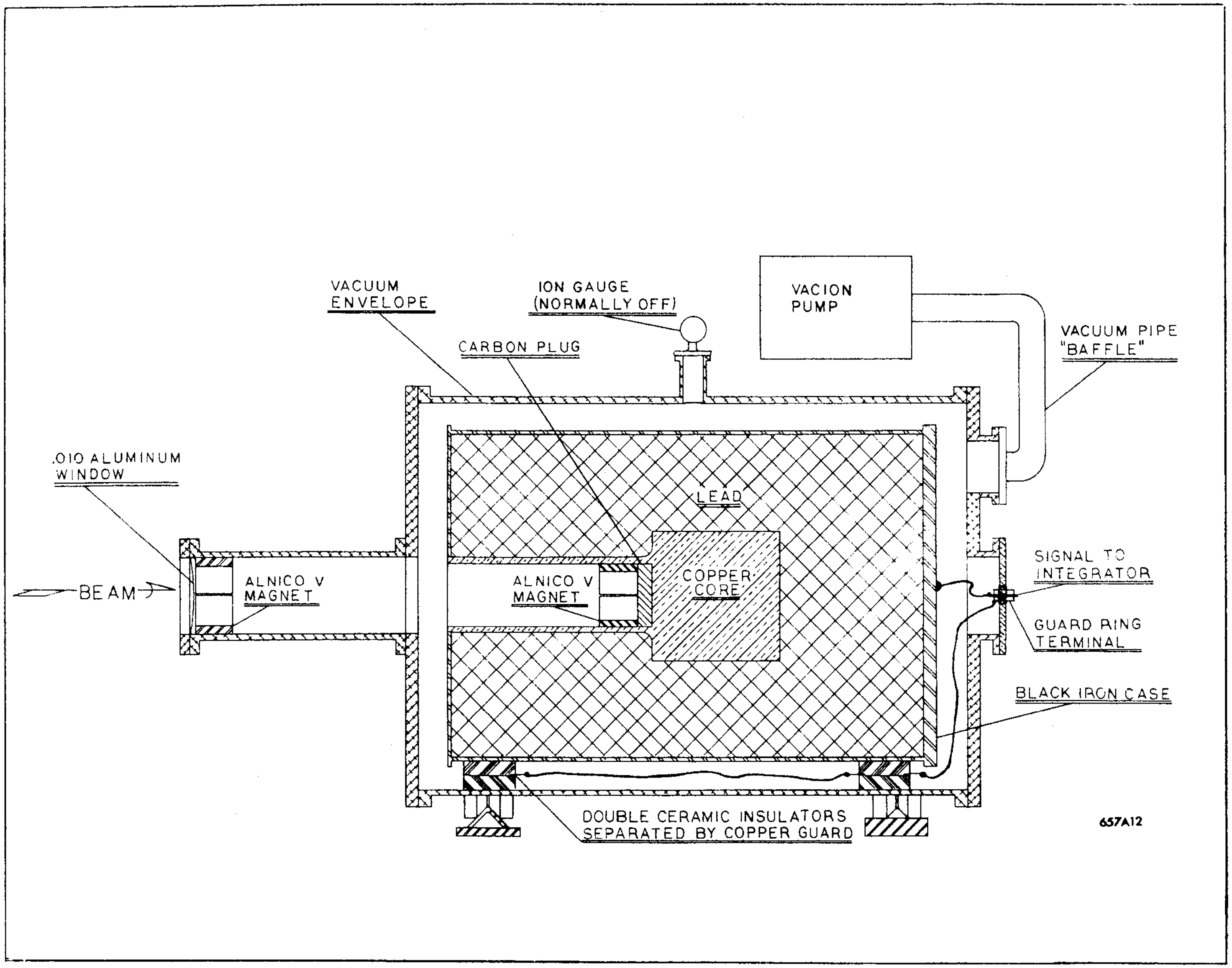

VACUUM ENVELOPE
ION GAUGE (NORMALLY OFF)
VACION PUMP
VACUUM PIPE "BAFFLE"
CARBON PLUG
.010 ALUMINUM WINDOW
LEAD
BEAM
ALNICO V MAGNET
ALNICO V MAGNET
COPPER CORE
SIGNAL TO INTEGRATOR
GUARD RING TERMINAL
BLACK IRON CASE
DOUBLE CERAMIC INSULATORS SEPARATED BY COPPER GUARD
657A12

Fig. 1

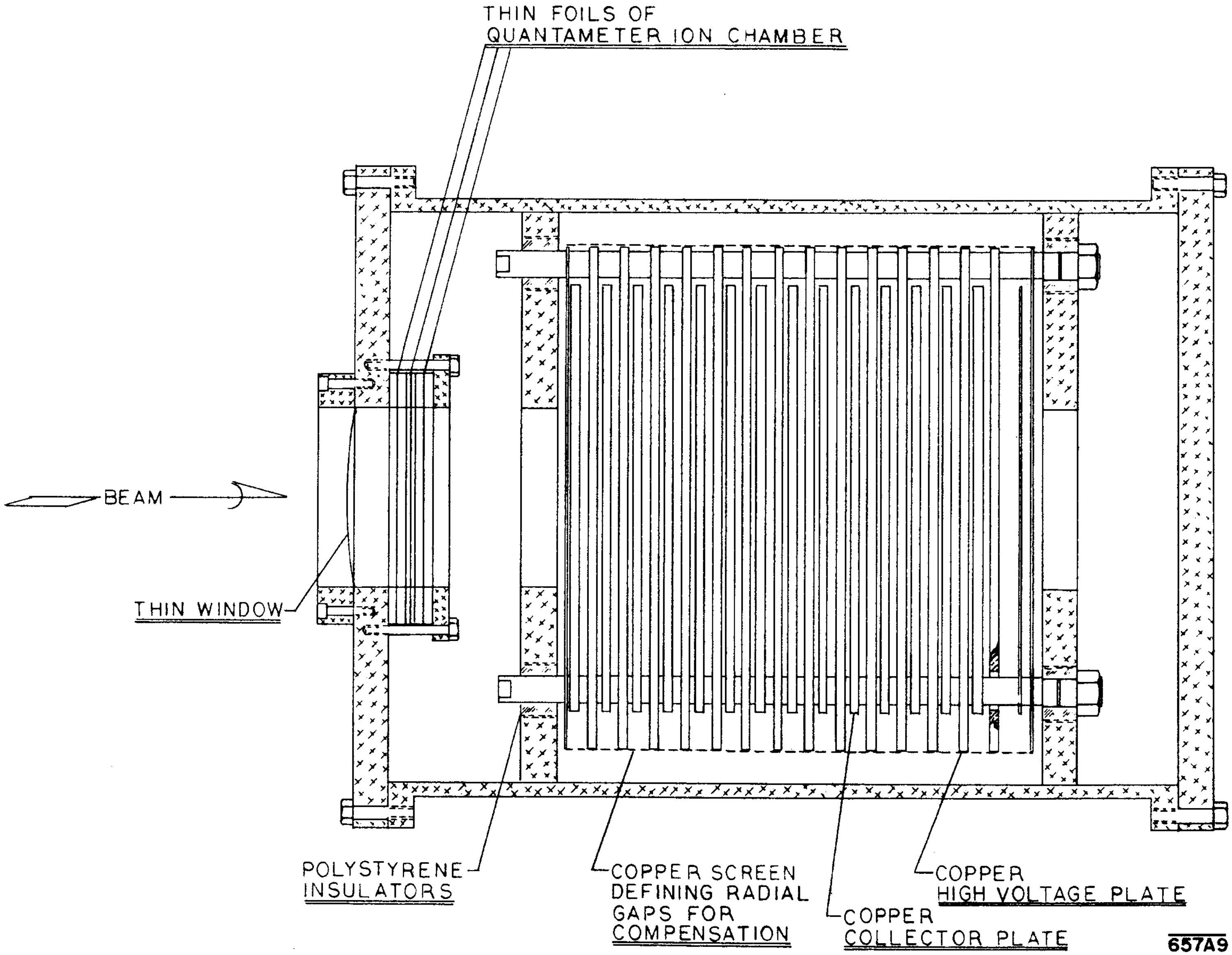

THIN FOILS OF
QUANTAMETER ION CHAMBER
BEAM
THIN WINDOW
POLYSTYRENE
INSULATORS
COPPER SCREEN
DEFINING RADIAL
GAPS FOR
COMPENSATION
COPPER
COLLECTOR PLATE
COPPER
HIGH VOLTAGE PLATE
657A9

Fig. 2

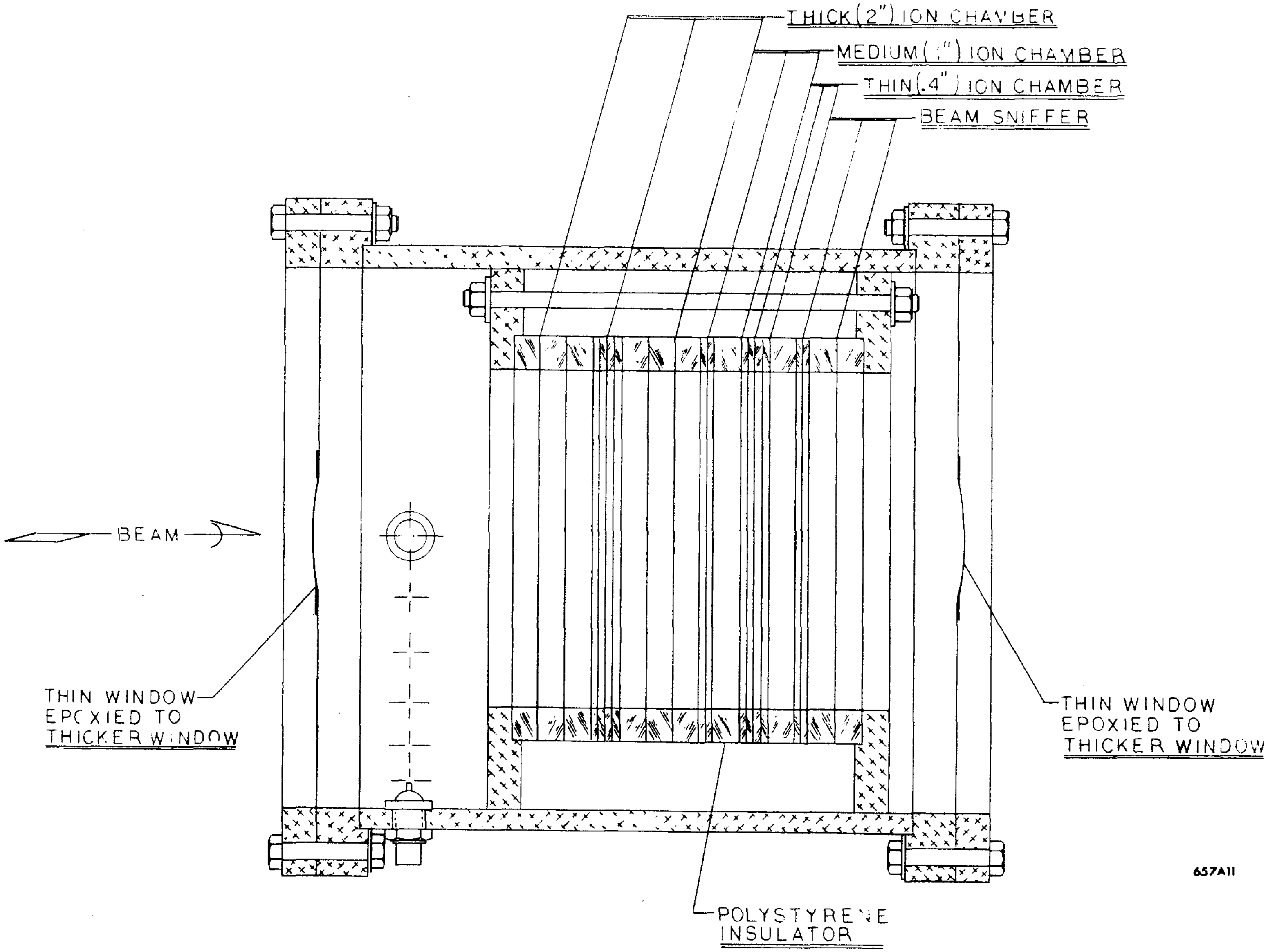
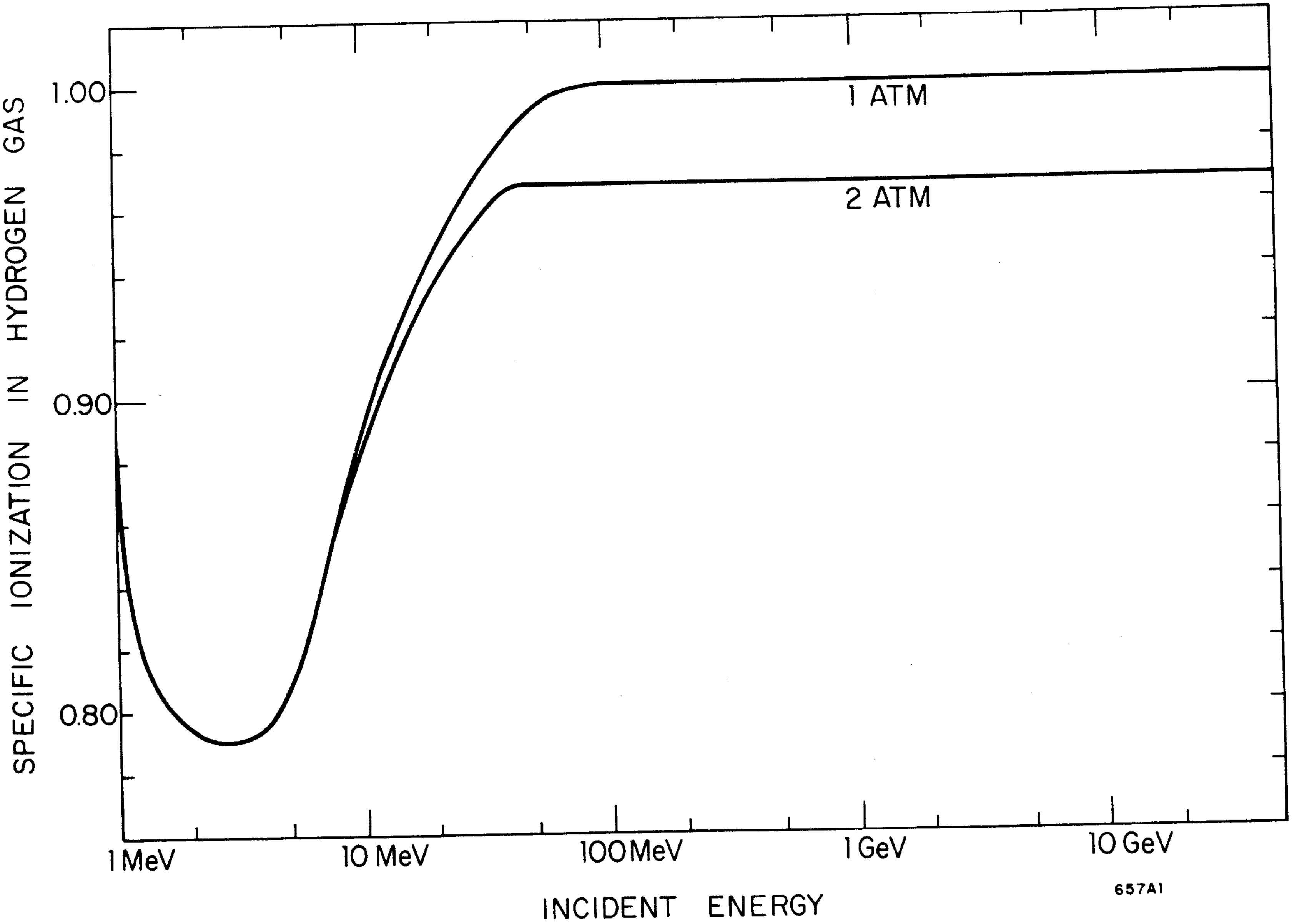
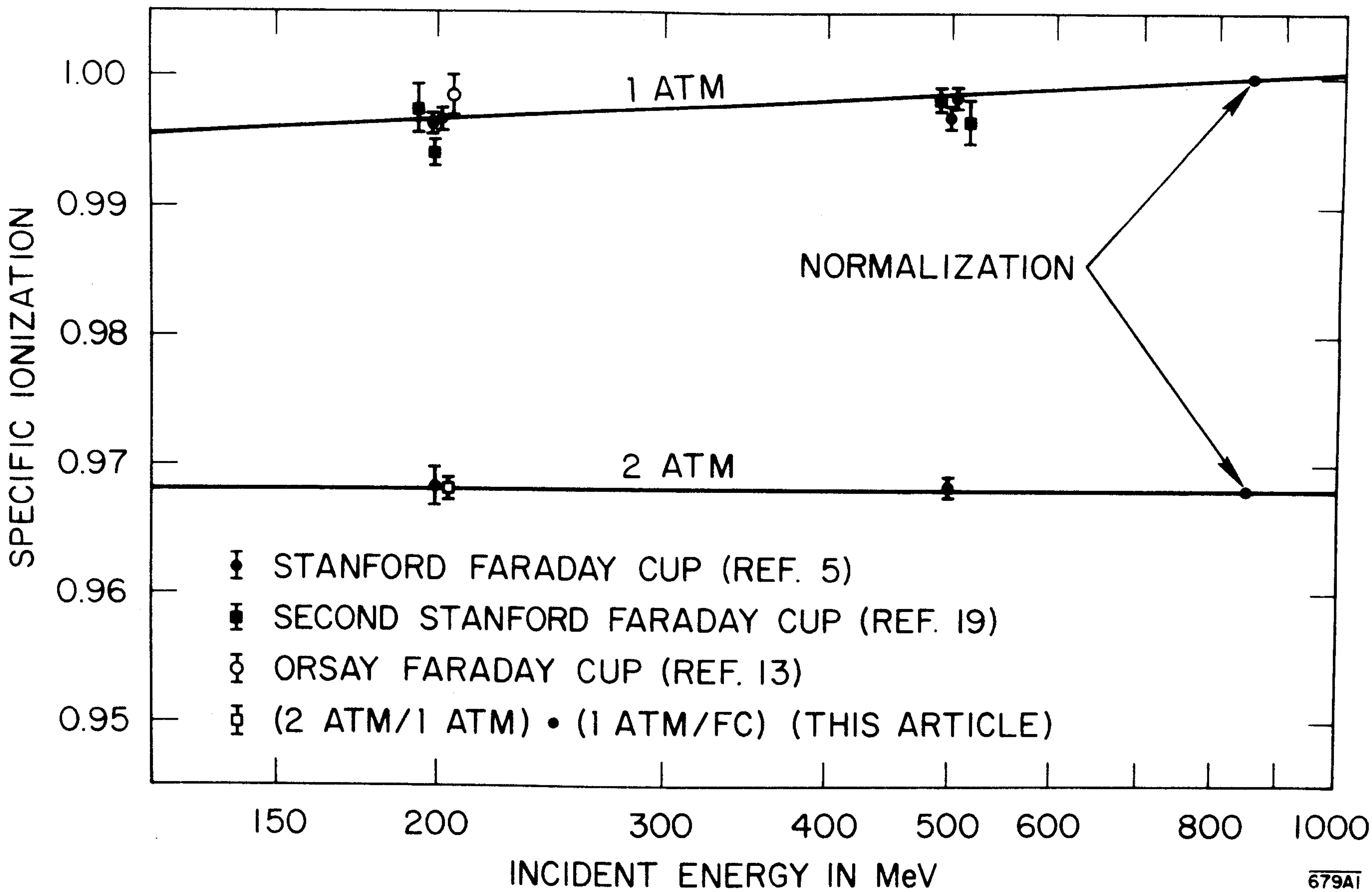

THICK (2") ION CHAVBER
MEDIUM (1") ION CHAMBER
THIN (.4") ION CHAMBER
BEAM SNIFFER
BEAM
THIN WINDOW EPOXIED TO THICKER WINDOW
THIN WINDOW EPOXIED TO THICKER WINDOW
POLYSTYRENE INSULATOR
657A11

Fig. 3



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. 4



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. 5

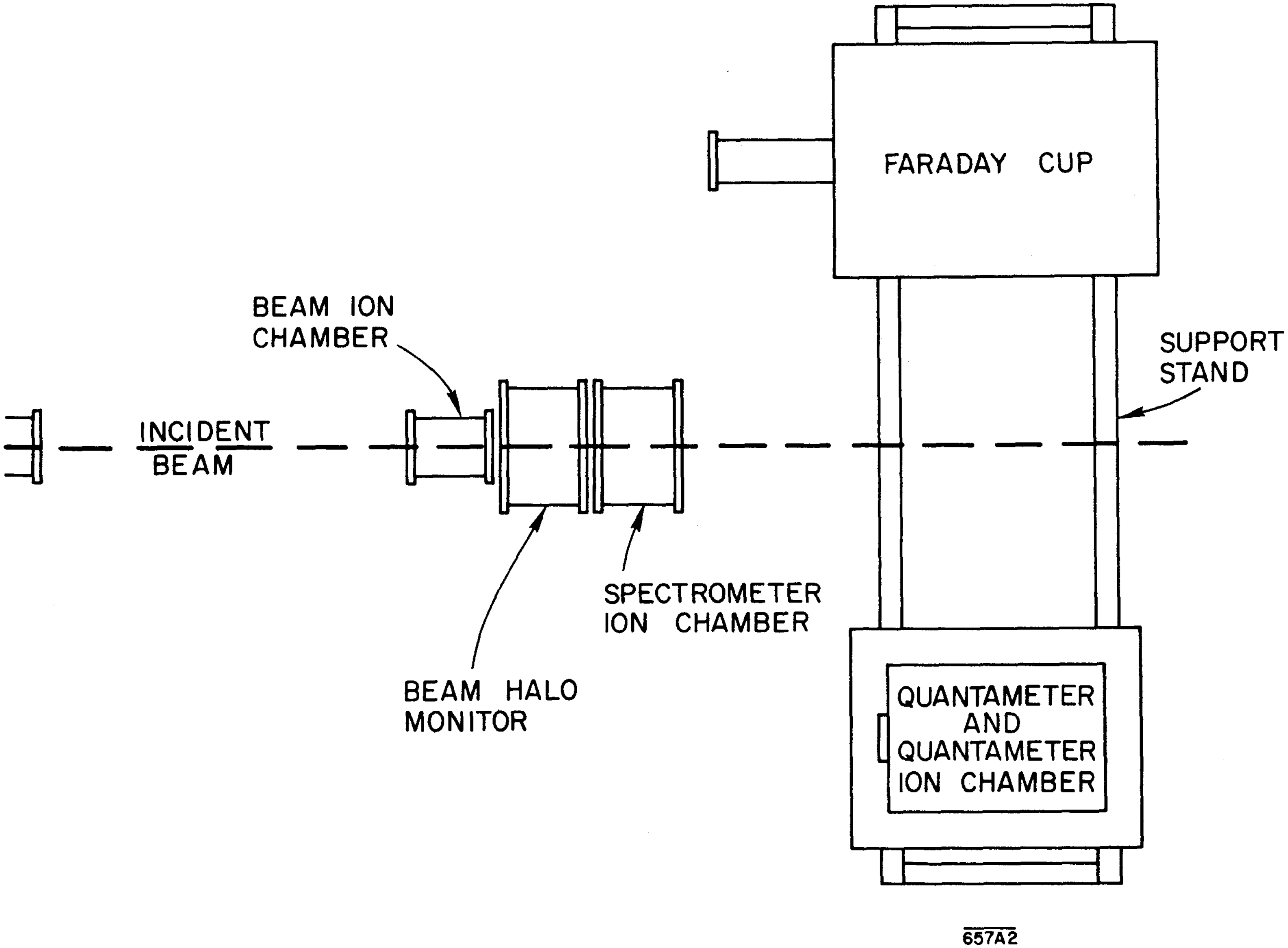
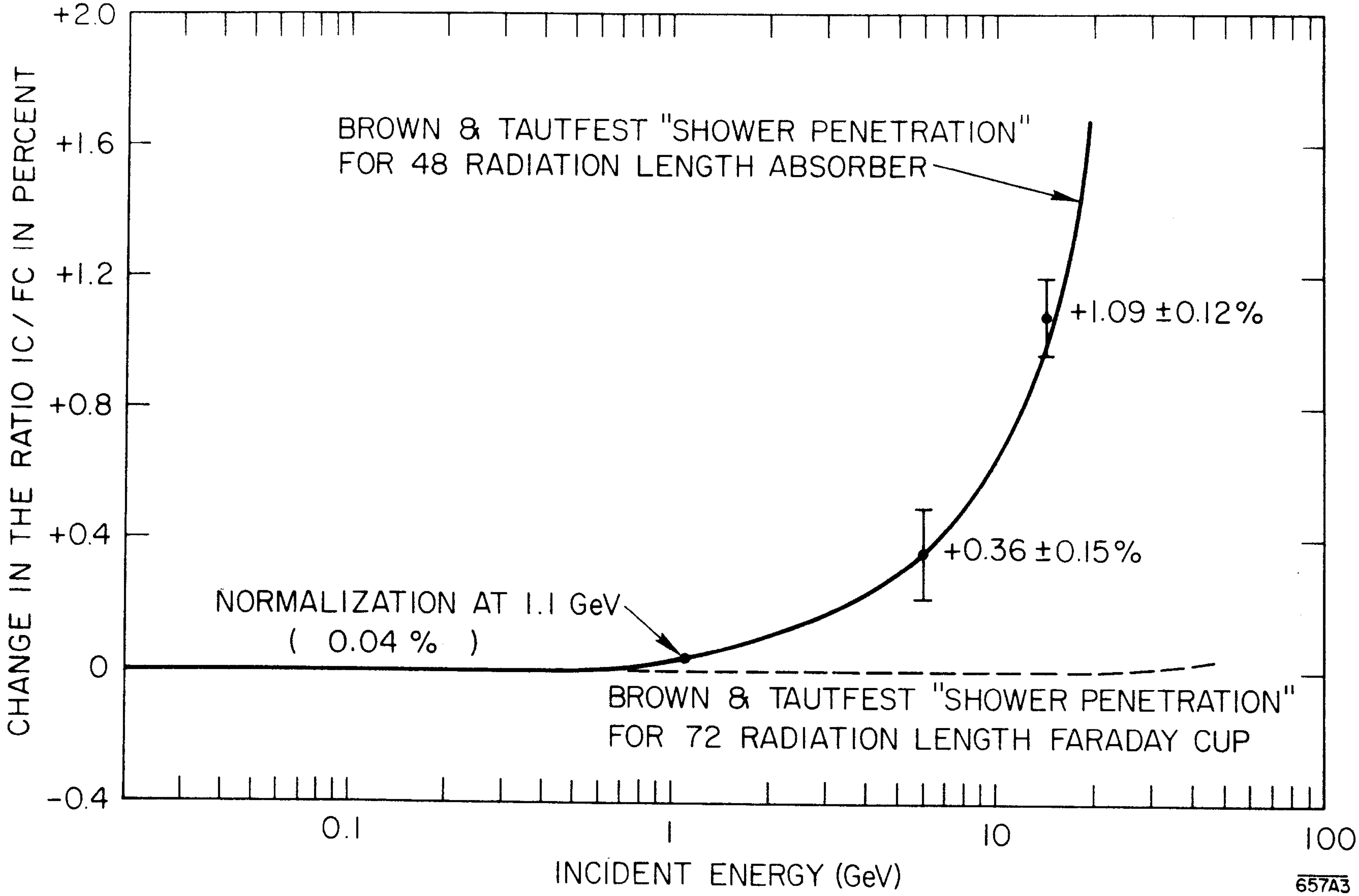

FARADAY CUP
BEAM ION
CHAMBER
SUPPORT
STAND
INCIDENT
BEAM
SPECTROMETER
ION CHAMBER
BEAM HALO
MONITOR
QUANTAMETER
AND
QUANTAMETER
ION CHAMBER
657A2

Fig. 6



CHANGE IN THE RATIO IC / FC IN PERCENT
+2.0
+1.6
+1.2
+0.8
+0.4
0
-0.4
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. 7

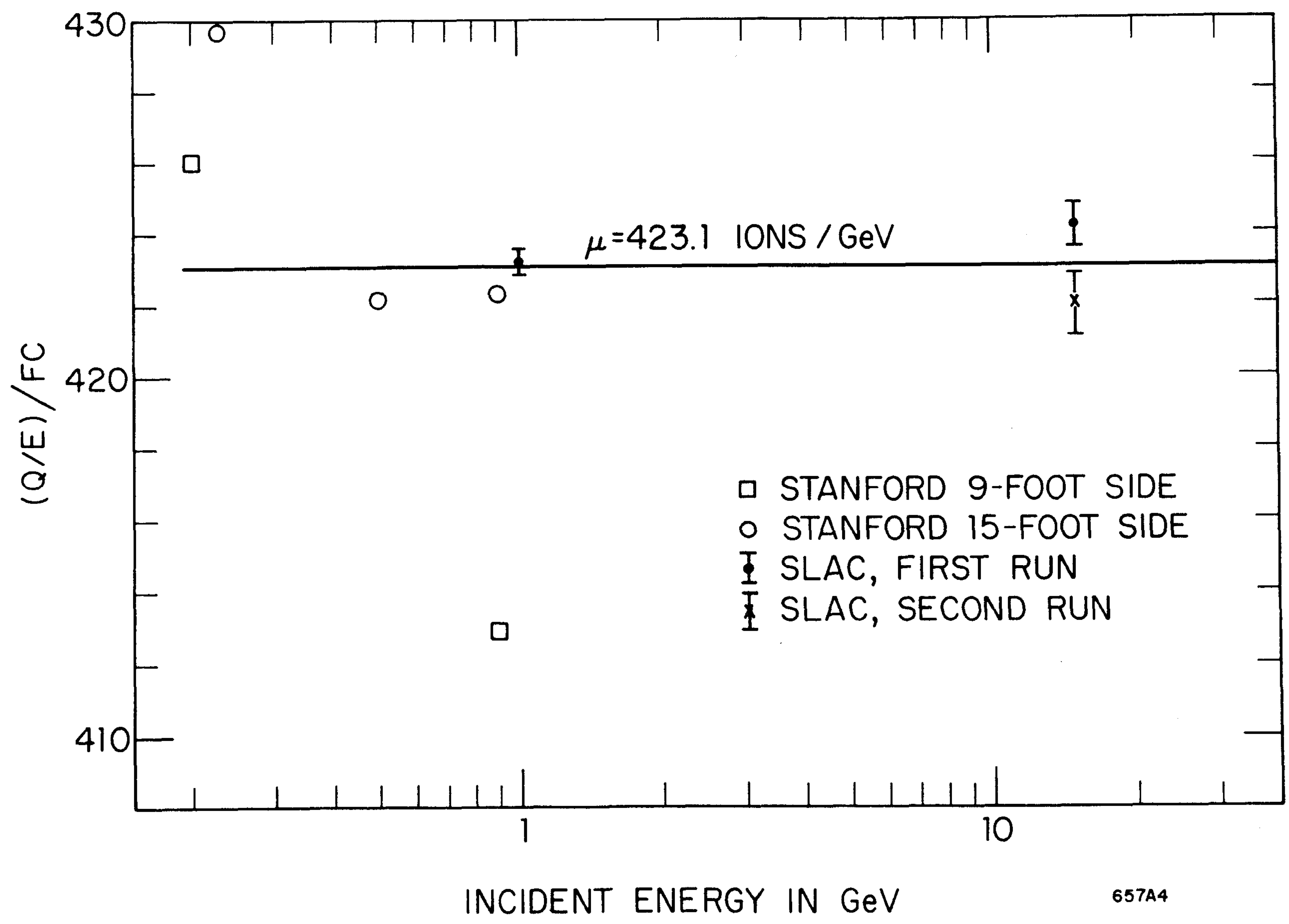
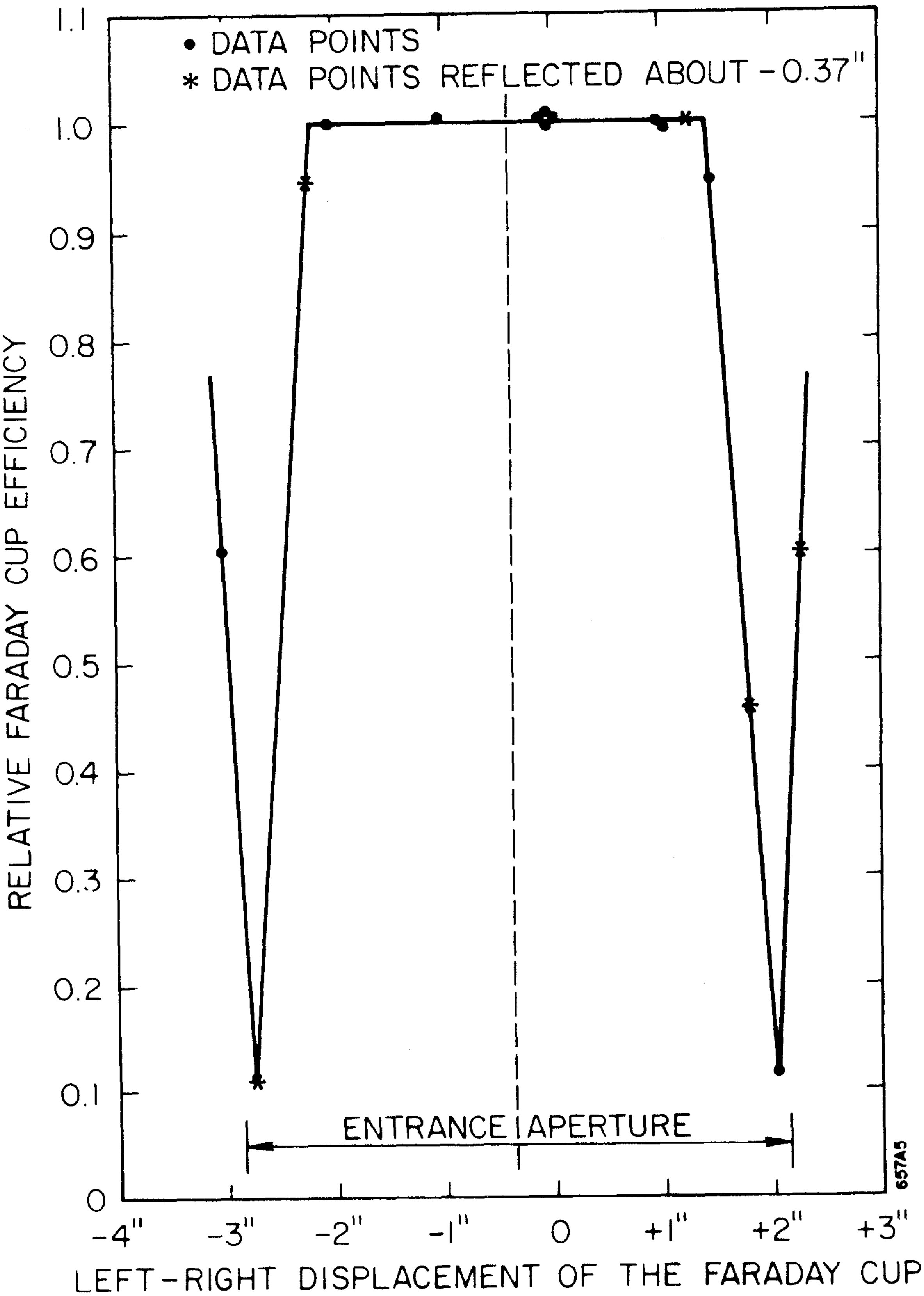
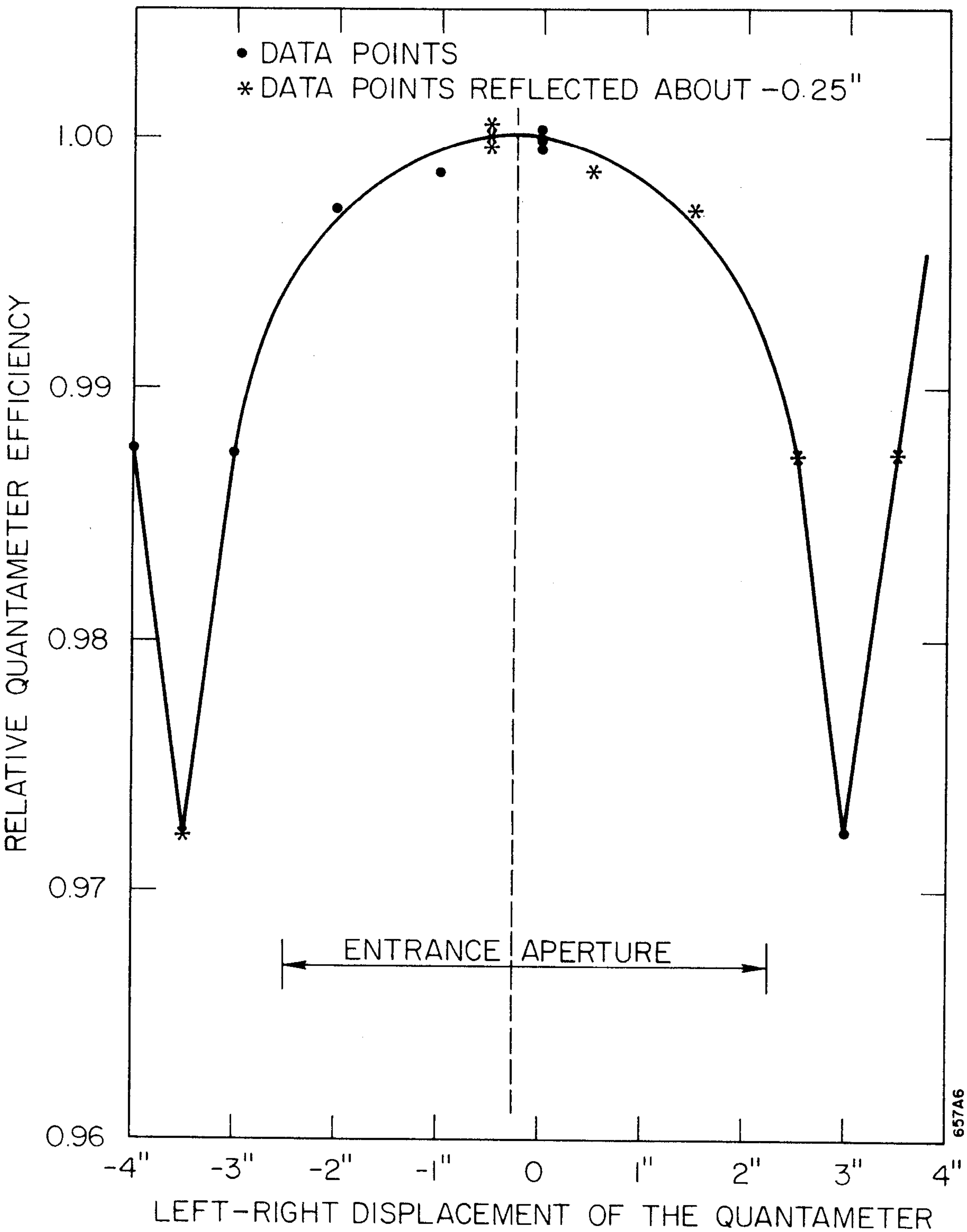

430
420
410
(Q/E)/FC
μ=423.1 IONS / GeV
STANFORD 9-FOOT SIDE
STANFORD 15-FOOT SIDE
SLAC, FIRST RUN
SLAC, SECOND RUN
1
10
INCIDENT ENERGY IN GeV
657A4

Fig. 8



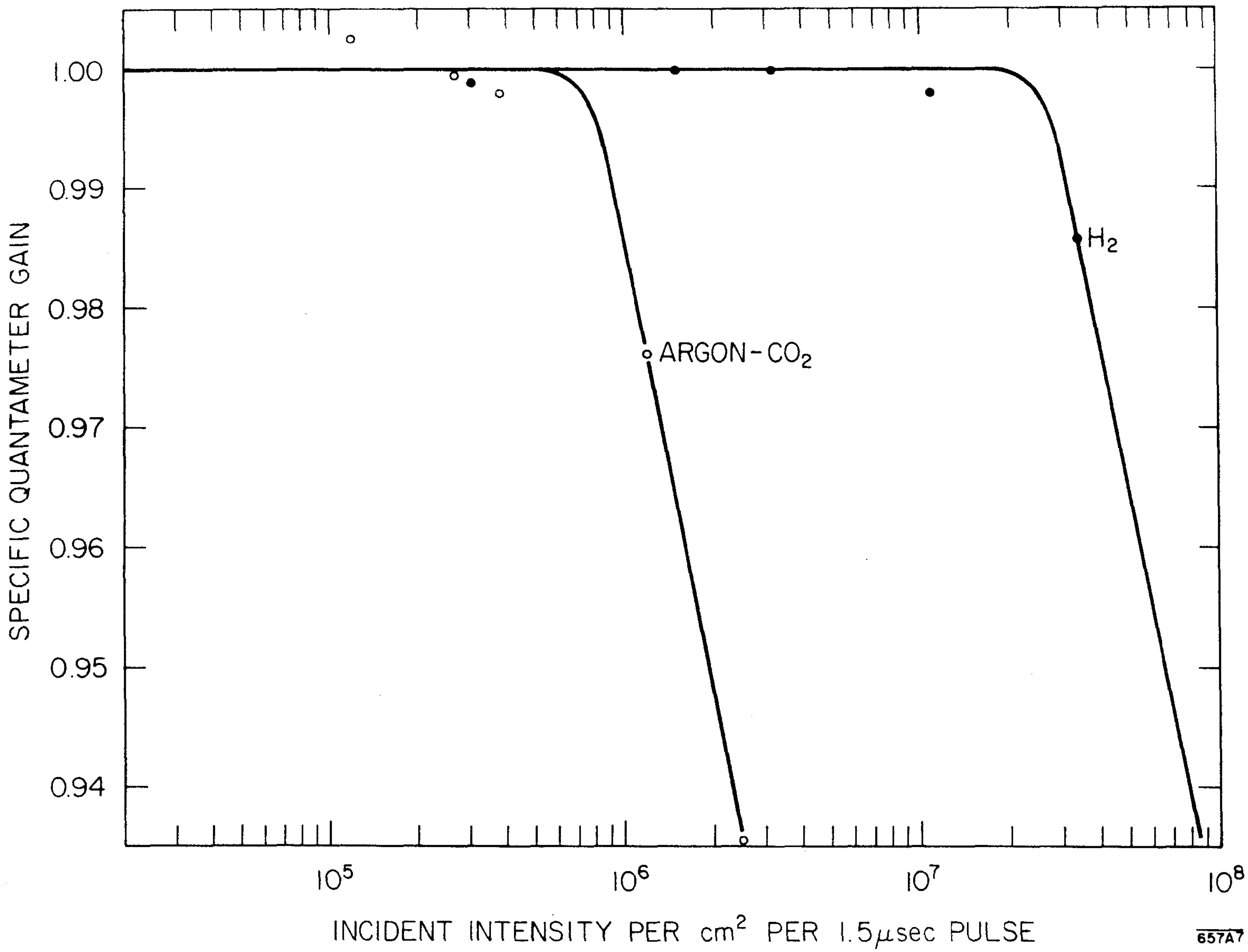
• DATA POINTS
* DATA POINTS REFLECTED ABOUT -0.37"
RELATIVE FARADAY CUP EFFICIENCY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ENTRANCE APERTURE
-4"
-3"
-2"
-1"
0
+1"
+2"
+3"
LEFT-RIGHT DISPLACEMENT OF THE FARADAY CUP
657A5

Fig. 9



• 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. 10



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

Fig. 11