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DIFFERENTIAL CERENKOV COUNTERS FOR USE AT HIGH MOMENTA*

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ABSTRACT

Design considerations for the fabrication and operation of differential Cerenkov counters at FNAL energies are given. Two counters now in operation in the Single Arm Spectrometer Facility at Fermilab are described. Fabrication details are given.

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I. INTRODUCTION

At FNAL energies of 50 to 300 GeV, hadrons are reliably identified with differential and threshold Cerenkov counters operating singly or in combination.[1,2,3] At 300 GeV/c, the velocity difference between pions and kaons approaches 1×10^{-6}. However, in spite of these small velocity differences, a much greater rejection of unwanted particles can, in practice, be achieved with Cerenkov counters than is usually required. Since these counters are expensive and large devices (10 to 15 m long), it is important to fully understand the design considerations and fabrication techniques so that the counter is a good match to the experiment for which it is to be used. For example, for a beam line, the counter system should have, in addition to high rejection, very high detection efficiences of unwanted particles so that unwanted particles coincident in time with a detected particle can be efficiently rejected. Cerenkov counter design criteria have been reviewed in the past.[3,4,5] However, the criteria needed for experiments in the 100 GeV range are sufficiently different that we give a brief review of optimum design criteria. Two counters have been built in accordance with these criteria and their fabrication and performance are discussed below.

The first counter constructed is now the differential counter of the Single Arm Spectrometer (SAS) facility of the Meson Laboratory at FNAL, and the second is now one of the differential Cerenkov counters of the M-6 beam line serving the SAS. Both counters are the same in principle but have significantly different design features. The second counter was built after the first was put into operation and although it is a simpler and cheaper counter, it is, on balance, a superior overall device.

II. GENERAL CONSIDERATIONS FOR DESIGN OF COUNTERS AT HIGH MOMENTA

A Useful Design Relation

The well-known Cerenkov relation, which relates the Cerenkov angle of the radiated photons, θ_c, the index of refraction of the medium n, and the velocity of the particle β is given by

$$\cos\theta_c = 1/\beta n ,$$

where $\eta = n(\lambda)$ and $\beta = \beta(p,m)$. We put this in a more useful form for work at high energies. For $m^2/p^2 < 1$

$$\beta = \frac{p}{E} \simeq 1 - 1/2\,\frac{m^2}{p^2} .$$

This approximation is good for momenta above 0.14, 0.5, and 1.0 GeV/c for pions, kaons, and protons, respectively. For a gas where $n \simeq 1$ and at low pressures

$$\eta \equiv n - 1 \simeq k \cdot \text{atm} ,$$

where atm is the pressure in atmospheres, and k is a constant of the gas. Both η and k vary slightly with the wavelength λ. k will also vary with pressure especially for highly refractive gases. Using these approximations, we get by substitution in the Cerenkov relation

$$\cos \theta_c \simeq 1 - \frac{\theta_c^2}{2} \simeq \frac{1}{\left(1 - \frac{1}{2}\frac{m^2}{p^2}\right)(1 + k \cdot \mathrm{atm})}$$

or

$$\boxed{\theta_c^2 = 2k \cdot \mathrm{atm} - \frac{m^2}{p^2} \quad .} \tag{1}$$

This is a most useful and practical relation. Almost all design considerations of Cerenkov counters above 1-2 GeV/c come from relatively simple manipulations of this formula. For example, the threshold pressure is obtained by setting $\theta_c = 0$, and is given by

$$\mathrm{atm(threshold)} = \frac{m^2}{2k \cdot p^2} \quad .$$

<u>Required Angular Resolution</u>

In a differential Cerenkov counter the Cerenkov light of angle θ_c is focussed by a high quality mirror, the primary mirror, to a ring of radius

$$\boxed{r = f\theta_c \ ,} \tag{2}$$

where f is the focal length of the mirror. Normally f is also the length L of radiating gas of the counter so ordinarily $f \simeq L$. At the focal point a slit system is placed to allow only the light of one radius to be accepted rejecting light at other radii due to other particles. The difference in Cerenkov angle θ_{12} between two particles of mass m_1 and m_2 at the same pressure and momentum is given by

$$\theta_1^2 - \theta_2^2 = \Delta(\theta^2) = 2\theta_c \Delta\theta_{12} = 2k\cdot\mathrm{atm} - \frac{m_1^2}{p^2} - 2k\cdot\mathrm{atm} + \frac{m_2^2}{p^2}$$

or

$$\boxed{\Delta\theta_{12} = \frac{m_2^2 - m_1^2}{2\theta_c p^2}\ .} \tag{3}$$

For 200 GeV/c and θ_c = 7 mrad (a practical achievable Cerenkov angle), $\Delta\theta_{12}$ = 0.4 mrad for πK separation, and 1.4 mrad for KP separation.

In practice the ring has a width

$$\Delta r = f\Delta\theta_c\ . \tag{4}$$

In order to resolve two particles of mass, m_1 and m_2, $\Delta\theta_c$ must be smaller than $\Delta\theta_{12}$, the difference in Cerenkov angle between the two particles. The width $\Delta\theta_c$ has several contributions:

$$\Delta\theta_c = \Delta\theta_\omega + \Delta\theta_B + \Delta\theta_{SCAT} + \Delta\theta_{MIR} + \Delta\theta_{\Delta p/p} + \Delta\theta_{DIF} \tag{5}$$

where

$\Delta\theta_\omega$ = variation in Cerenkov angle due to the variation of η with wavelength. At high energies this term usually dominates.

$\Delta\theta_B$ = variation of the angles in the beam.

$\Delta\theta_{SCAT}$ = variation of particle angles due to multiple scattering in the counter.

$\Delta\theta_{\Delta p/p}$ = variation of θ_c due to the momentum acceptance of the beam transport system. This is negligible at high energies.

$\Delta\theta_{DIF}$ = diffraction limit of counter. This is small for our consideration.

Chromatic Angular Dispersion

The variation of η with wavelength can be sufficiently large so that there is a significant dependence of θ_c on λ. Rewriting Eq. (1), we get, letting $\eta = k \cdot \mathrm{atm}$

$$\eta(\lambda) = \frac{\theta_c^2}{2}\left(1 + \frac{1}{\frac{p^2}{m^2}\theta_c^2}\right). \tag{6}$$

The variation of η with λ is referred to as the dispersion. The dispersive power of a medium $\lambda_2 - \lambda_1$ is defined to be

$$\omega = \frac{\eta(\lambda_2) - \eta(\lambda_1)}{\eta_{avg}} .$$

For the wavelength response of a phototube, $\omega \sim 5 - 20\%$ for the gases of interest. ω is the reciprocal of Abbe's number. Differentiating the Cerenkov relation

$$-\sin\theta d\theta = \frac{1}{\beta}\frac{dn}{n^2} \simeq \frac{d\eta}{\eta}\frac{\eta}{n^2} \simeq \omega\eta$$

since $n \simeq \beta \simeq 1$ and $\sin\theta \sim \theta$ we get

$$\theta_c \Delta\theta \simeq \omega\eta .$$

Substituting this in Eq. (6), we obtain the chromatic angular dispersion of the Cerenkov light $\Delta\theta_\omega$ to be

$$\boxed{\Delta\theta_\omega = \frac{\theta_c\omega}{2}\left(1 + \frac{1}{\frac{p^2}{m^2}\theta_c^2}\right).} \tag{7}$$

At the higher energies (above 15 GeV for pions, 100 GeV for protons) for reasonable Cerenkov angles, the second term is negligible, and we get simply

$$\Delta\theta_{\omega} = \frac{\theta_c \omega}{2} \quad . \tag{7a}$$

For $\theta_c = 7$ mrad and $\omega = 4.5\%$ (helium), $\Delta\theta_{\omega} = 0.125$ mrad.

Maximum Possible Momentum

At high energies, where the angular separation of the Cerenkov light from two particles, $\Delta\theta_{12}$, is very small, the chromatic angular dispersion limits the resolution of the counter and the highest momentum the counter can hope to operate at is given when $\Delta\theta_{12} = \Delta\theta_{\omega}$. From (3) and (7a) we get for this condition

$$\frac{m_2^2 - m_1^2}{2\theta_c p^2} = \frac{\theta_c \omega}{2}$$

or rearranging

$$\boxed{p_{max}^2 = \frac{m_2^2 - m_1^2}{\theta_c^2 \omega} .} \tag{8}$$

For kaons and pions, for helium ($\omega = 4.5\%$), and $\theta = 7$ mrad, we get a limiting momentum of 360 GeV/c and 604 GeV/c for protons. From (8), we see that, in order to operate at as high a momentum as possible, the counter should be designed to operate at as small a Cerenkov angle as possible and still give sufficient light for reasonable efficiency. And, of course, one should pick a gas such as helium which has the smallest dispersion ω. It is possible to optically correct for the chromatic dispersion ω, allowing one to operate at larger Cerenkov angles. However, up to ~ 200 GeV/c, this is not necessary.

Photoelectron Yield

The number of photons, N_{γ}, emitted in a length L between wavelengths λ_2 and λ_1 at a Cerenkov angle θ_c is

$$N_\gamma = 2\pi\alpha L\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\sin^2\theta_c \quad . \tag{9}$$

For $\lambda_2 = 2000$ Å and $\lambda_1 = 5000$ Å, the approximate range of quartz photomultipliers, we get

$$N_\gamma = 1375\ L\sin^2\theta_c \quad .$$

Assuming a photo-cathode efficiency of 25% and a light collection efficiency of 80%, we get the number of photoelectrons, N_e, from the photo-cathode (letting $\sin^2\theta_c \approx \theta_c^2$) to be

$$N_e = 275\ L\,\theta_c^2 = N\,L\,\theta_c^2 \quad .$$

In practice, the best we have achieved for this constant, N, is 168, indicating the photo-cathode efficiency is less than 25% averaged over the whole range of wavelengths. From our experience, it seems safe to assume N = 150 for design considerations, assuming one obtains the best tubes available. Thus

$$\boxed{N_e = 150\,L(\mathrm{cm})\,\theta_c^2\ .} \tag{10}$$

For our counters we were able to let L be 10 and 13 meters. For a Cerenkov angle of 7 mrad and L = 10 meters we get N_e = 7.3 mrad. If the counter is set to count one photoelectron, assuming Poisson statistics the counter will be 99.9% efficient.

Beam Divergence

If $\Delta\theta_B$ is the angular divergence of the particles being detected, we must require

$$\Delta\theta_B < \Delta\Theta_{12}$$

in order to resolve the Cerenkov light from the two particles. If this requirement is not met, either the resolution or the efficiency of the counter will suffer, or the maximum momentum is restricted below that which the counter is capable of operating. Thus for θ_c = 7 mrad, p = 200 GeV/c, $\Delta\theta_B$ is required to be less than

0.4 mrad for πK and 1.4 mrad for KP separation.

Determination of Index of Refraction

At high energies the accuracy required in the determination of η can become prohibitive. The required accuracy can be reduced if one is able to operate at smaller Cerenkov angles. Differentiating (1) at constant p we get

$$\theta_c d\theta = k \cdot d(atm) \; . \tag{11}$$

At high momenta the second term in (1) can be neglected giving

$$\theta_c^2 \simeq 2k \cdot atm = 2\eta \; . \tag{12}$$

Dividing (11) by (12) we get the accuracy required of the pressure, or the index of refraction, since the two are proportional

$$\frac{d\eta}{\eta} = \frac{d(atm)}{atm} = \frac{2d\theta}{\theta_c} \; . \tag{13}$$

Letting $d\theta = \Delta\theta_{12}$, the angular resolution necessary to separate two particles, we get

$$\frac{d\eta}{\eta} = \frac{m_2^2 - m_1^2}{\theta_c^2 p^2} \; . \tag{14}$$

Thus we see as θ_c is reduced the required accuracy in the determination of η (and the pressure) is rapidly reduced. Since for constant volume

$$\frac{dT}{T} = \frac{d(atm)}{atm}$$

we see a similar gain is made in the determination of the temperature T. For example for 200 GeV/c and θ_c = 7 mrad the accuracy necessary to separate pions and kaons is only 11%. Even allowing a safety factor of 10 the accuracy required is only 1%. This corresponds to $3^{\circ}C$ change in temperature, an easy temperature difference to measure.

Coma and Spherical Aberration

The coma and spherical aberration of the primary mirror is given by

$$\Delta\theta_s = \theta_c^3 \quad . \tag{15}$$

If we require

$$\Delta\theta_s < \Delta\theta_{12} \ ,$$

we get from (3)

$$\theta_c^4 < \frac{m_2^2 - m_1^2}{2p^2} \ .$$

For 200 GeV, for pions and kaons we get

$$\theta_c < 41 \text{ mrad} \ .$$

If we require a safety factor of 10, we get

$$\theta_c < 23 \text{ mrad} \ .$$

This aberration can be corrected optically but is unnecessary if one keeps θ_c sufficiently small.

Mechanical Tolerances and Alignment

From Eq. (2) the accuracy of determining the position of rings of Cerenkov light is given by

$$\Delta r = f\Delta\theta_c \ .$$

If we require $\Delta\theta_c \leq \Delta\theta_{12}$ from (3), we get

$$\Delta r = L \frac{m_2^2 - m_1^2}{2\theta_c p^2} .$$

Again for $\theta_c = 7$ mrad, $p = 200$ GeV and for $L = 10$ m we get

$$\Delta r_{\pi K} = 0.4 \text{ cm}$$

and

$$\Delta r_{kp} = 1.4 \text{ cm}$$

distances that are of reasonable magnitude.

The alignment of the counter or the primary mirror is also determined by $\Delta\theta_{12}$. For 200 GeV and $\theta_c = 7$ mrad the separation for pions and kaons we get

$$\Delta\theta_{12} = 0.4 \text{ mrad},$$

an easy alignment angle to achieve.

Quality of Primary Mirror

From (3) and (4) we get the separation of the rings of light at the focal point of the primary mirror for two different mass particles to be

$$\Delta r = f\Delta\theta_{12} = f \frac{m_2^2 - m_1^2}{2\theta_c p^2} .$$

The circle of confusion (or resolution) of the mirror must be smaller than this. Operating at small θ_c makes less demands on the required figure of the primary mirror. We will see for the counters described here a figure of 1λ is required. An astronomical mirror is normally figured to $\lambda/13$ (diffraction limited).

Size of Phototube

At present the best phototubes are 5 cm in diameter. Thus, there is a premium on focussing the light onto a ring of sufficiently small diameter. The radius of the disk of light is given by the focal length of the light collecting mirror times the sum of the Cerenkov angle and the spherical aberration angle. The variation of θ_c due to astigmatism of the mirror is given by the cube of the tilt angle of the mirror, thus[3]

$$r = f(\theta_c + \theta^3_{tilt}) .$$

For f = 60 cm, θ_c = 7 mrad and $\theta_{tilt} = 10^o$ we get

$$r = 60(.007 + .0053) = 0.74 \text{ cm} .$$

Thus, by keeping θ_c and θ_{tilt} small one can easily focus all of the light onto one 5-cm phototube.

III. CONCEPTUAL DESIGN

Figure 1 is a simplified drawing showing the principle of differential Cerenkov counters we have built for use at high energies. Referring to the figure, beam particles come from the left along the axis of the counter passing through the thin portions of the light collecting mirrors, continuing through the radiating gas for a length L, and finally passing through the thin-portion of the primary mirror. The Cerenkov light forms a ring at the focal point of the primary mirror with a radius

$$r_c = f\theta_c .$$

At f we place a light collecting mirror with an annulus removed to allow only light from the particle to be detected to pass through. The light passing through the annulus is reflected by a second mirror onto a photomultiplier referred to as the ring or coincidence tube. Light from particles of different mass or from background particles is reflected onto the veto photomultiplier allowing these particles to be rejected. The ability to veto unwanted particles with high efficiency is of prime importance when the counter is being used to detect minority particles in a beam of high intensity. The majority particles in this case can occur in the same instant of time as the particle being detected and even though the counter did not detect it, it will appear to be counted. This becomes especially important when the counter is used as a beam counter where intensities can be very high, and it is important that the counter count the particles of interest and rejects all other particles in the same time slot.

From the previous discussion it is clear the counter for use at high momentum should be designed with the Cerenkov angle θ_c as small as possible, making L large. Of course, one will want to be able to change θ_c occasionally by adjusting the radius r of the annulus. Also one will want to be able to adjust Δr, the width of the annulus. For the two counters described here we made L = 10 and 13 meters allowing the counters to fill the available space.

It is very helpful for design purposes and for understanding the operation of the counters to know r_c for pions, kaons and protons as a function of momentum. It is also useful to have also Δr_c, the spread in Cerenkov angle. Figure 2 gives an example of a set of graphs of these quantities where the Cerenkov angle of the detected particle is θ_c = 8.5 mrad with helium as the radiating gas. For f=10 meters one mrad corresponds to 1 cm at the focal point, so the vertical scale also reads directly the radius of the ring of light in centimenters.

In addition Figure 2a gives the operating pressure for each particle for 8.5 mrad. At high momenta we see the operating pressure for all particles is 1 to 2 atmospheres. From Eq. (1) we see the pressure of the gas goes as θ_c^2. Thus, operating at larger Cerenkov angles requires stronger pressure vessels and thicker windows. For low momenta the operating pressures with helium become prohibitively large and a more refractive gas such as nitrogen is used. Figure 3 gives a set of curves for operating pressures and corresponding Cerenkov angles for nitrogen. We see with nitrogen above 140 GeV we can no longer hope to resolve pions and kaons because of the larger chromatic dispersion. However, at low momenta nitrogen is a good choice.

Figure 4 gives a set of curves for helium at 10 mrad. At this angle even with helium we can no longer resolve pions and kaons above 180 GeV/c. However, protons are easily resolved at all energies. The 13-meter counter which was built primarily to detect protons was designed with this set of curves in mind.

IV. THE 10-METER COUNTER

General Description

Figure 5 is a drawing of the 10-meter counter. The focal length of the primary mirror is 9.74 meters making the overall length 11 meters. For this focal length a change in Cerenkov angle of 1 mrad corresponds closely to a 1 cm displacement at the focal point of the primary mirror. At the focal plane, the counter has a remotely rotatable wheel on which six different mirrors can be placed (see sectional view in Fig. 5). Each mirror has an annulus of different dimensions removed. Additional mirrors can be installed by removing the cover plate. The horizontal and vertical angles of the primary mirrors can be changed remotely and read out to an accuracy ± 0.05 mrad, which corresponds to a movement at the focal plane of ± 0.05 cm.

Light of the correct Cerenkov angle passes through the annulus of the veto mirror. This light is reflected through 20° by the coincidence mirror (f = 58 cm) and after passing through a quartz window is detected by a single two-inch diameter RCA8850 quartz-faced photomultiplier (C31000M). The light is focussed to a disk at the face of the phototube of about 1 cm in diameter (see Fig. 10). Light produced by a particle of the wrong mass or by a background particle is reflected to the veto photomultiplier also through 20°.

Light Collecting Mirror

The mirror wheel allows six different mirrors to be remotely moved into position. However, it is not possible to anticipate all possible mirrors that might be required. Thus, we intended from the beginning to change the mirrors on the wheel as different annuli were needed, it was important to be able to make these mirrors quickly and cheaply. We have provided 15 mounts for the mirrors and 30 blank mirrors that could be used to fabricate mirrors with different annuli. The mounts are coded allowing one to remotely sense which mirror is in which position of the wheel to avoid possible confusions. The annuli are slightly elliptical rather than perfect circles since the mirrors are placed at 10° relative to the axis of the counter. Since the angular astigmatic aberration associated with the angle of the mirrors is $\pm\ \theta^3$ where θ is the tilt angle of the mirrors, it is important to keep this angle small so that the disk of light remains focussed inside the two-inch diameter of the phototube. This effect is clearly shown in Fig. 10. Also the tilt of the mirror allows part of the annulus to not be at the exact focal point of the primary mirror. This effect could contribute to the resolution of the counter if allowed to be too large but is negligible at 10°.

Primary Mirror Alignment Systems

Two design features are indicated in Fig. 5, which allow one to align the primary mirror with the axis of the counter without the use of beam particles.

1. Telescope System

An autocollimating telescope mounted at right angles to the counter is adjusted to sight along the axis of the counter by use of a removable 45^{o} mirror. In the center of the alignment position of the mirror wheel, a cross hair is mounted that can be illuminated. The alignment procedure is as follows:

a. Align the telescope optically along the axis of the counter.

b. Focus on the cross hair.

c. Focus on the reflection of the cross hair and adjust the angle of the primary mirror until the two images coincide.

This alignment can be made to ± .05 mrad but requires some skill in using the telescope.

2. Photoresistor System

This system allows the alignment to be done remotely and requires less skill than the telescope system. Also mounted in the alignment position of the mirror wheel is a point light source that can be positioned along the axis of the counter. The image of this source from primary mirror reflects back as a disk, the diameter of the primary mirror. This disk of light can be accurately centered by use of 4 photoresistors and some balancing circuitry. The system is simple to use and gives at least as accurate result as obtainable with the telescope.

Both systems work and were invaluable in understanding the counter before we were able to test it with real particles. However, once the counter is in a beam line with real particles, the primary mirror can be aligned easily relative to the axis of the beam, the axis with which it must ultimately be aligned.

Operating Pressure

For $\theta_c = 7$ mrad for helium the pressure of the counter is just below 1 atmosphere so that the counter is sensitive to small leaks. Helium is 8.5 times less refractive than air and air contains oxygen which is ultraviolet absorbing. To avoid possible leaks, we chose to operate initially at 8.5 mrad which places the operating pressure a few pounds above 1 atmosphere although the counters best performance would be at 7 mrad.

Temperature Regulation

From Section II we see that the temperature regulation is not critical. We were concerned that as the pressure is changed that the counter would distort slightly as the temperature changes. To avoid temperature effects we made the counter out of aluminum because of its high conductivity, wrapped the counter in thermal insulation, and water-cooled the counter to hold the counter at one temperature.

Low Momentum Operation

At low energies the pressure of helium becomes large so that a more refractive gas is used. The maximum operating pressure of the counters is 75 PSIA. Nitrogen is a convenient choice. Figure 3 shows the pressure and Cerenkov angles for nitrogen. The chromatic angular dispersion is greater with nitrogen requiring an annulus of larger width; however, the separation between particles becomes very large at these energies so this does not limit the operation of the counter. This can be seen by comparing Fig. 3 and Fig. 2. At very low momenta one might want to run entirely without a veto mirror. We have operated the counter in this broad band mode successfully.

V. THE 13-METER COUNTER

This counter is very similar to the 10-meter counter (see Table I for a comparison between the two counters). It is longer, $f = 1293$ cm, and its total length is 13.9 meters (see Fig. 6). It does not have the feature of being able to remotely change the annulus by use of the mirror wheel as the 10-meter counter. However, the counter has been fabricated so that the mirrors can be changed in a relatively short time. To do this, one removes the cover plate above the veto mirrors and the assembly on which the mirror is mounted is raised by aid of a counter weight, and the mirror and its holder can be removed and changed with no alignment necessary.

The counter was designed with its primary purpose to detect protons in the beam line. Since the separation in Cerenkov angle between protons, and pions and kaons is large even at 200 GeV/c, one can operate the counter at a larger Cerenkov angle such as 10 mrad. Figure 4a gives a set of curves similar to Fig. 2 except for Cerenkov angle of the detected particle set for 10 mrad. Above 180 GeV/c pions and kaons are not resolvable. Here the number of photoelectrons is 19. Because of this large number of photoelectrons we could split the light collecting mirror requiring a coincidence between two phototubes obtaining a higher rejection against background particles. Figure 7 shows the efficiency of the counter versus the number of photoelectrons, assuming the phototubes are 100% efficient for one photoelectron. The curve labeled 1-FOLD assumes the pulses from the tubes are added. The curve labeled 2-FOLD assumes a coincidence is made between the two tubes. We see the counter is better than 99% efficient with 5 photoelectrons for the pulses added and 11 photoelectrons with a coincidence required.

VI. CONSTRUCTION DETAILS

Mirrors

Two types of mirrors are employed in the differential counters described here, primary focussing mirrors and secondary light collecting mirrors. Both types should have high reflectivity into the ultraviolet since quartz-faced tubes have a response extending to 1900 Å. Evaporated aluminum (~1000 Å) gives the best ultraviolet response. A 400 Å thick coating of magnesium floride not only protects the surface but will also extend the response into the ultraviolet. Such a mirror has above 85% reflectivity in the range 1800 Å to 4000 Å with an average reflectivity of 88%.

1. Primary Mirrors

At high energies the resolution required approaches that of an astronomical mirror although the mirror need not be of such high quality that it is diffraction limited. The separation between two rings of Cerenkov light, which determines the resolution is given by

$$\Delta r_c = f \Delta\theta_c \quad ,$$

where $\Delta\theta_c$ is given by Eq. (3). If we require the circle of confusion due to the quality of the mirrors to be 1/5 this separation, we get substituting $\Delta\theta_c$ from Eq. (3)

$$\Delta r = 1/5 \; f \frac{m_2^2 - m_1^2}{2p^2\theta_c} \quad .$$

For πk separation an energy of 200 GeV, $\theta_c = .007$, and f = 10 meters we get for the required diameter of the circle of confusion to be Δr = 0.8 mm, which is large compared to the radius of the circle of confusion of a diffraction limited mirror. The radius of the first trough in the diffraction pattern of a mirror is given by

$$x_1 = \frac{1.22\lambda f}{D} \quad ,$$

where D is the diameter of the mirror. For f = 10 meters, λ = 4000 Å and D = 30 cm we get

$$x_1 = 0.016 \text{ mm} \quad ,$$

which is much smaller than 0.8 mm. To be diffraction limited 70% of the light should be within x_1 (this corresponds to an rms deviation of the figure of the mirror of $\lambda/13$). Thus, the mirror is far from diffraction limited.

To avoid excessive multiple scattering in the primary mirror, the mirror must be made with a hole or with a very thin section in the center. We have made mirrors both ways for the counters allowing one to change them if one desires the advantages of either mirror. The thin section for the 10-meter counter is 2.5 mm thick and 7.5 cm in diameter. In order that the mirrors hold the figure during temperature changes of the Cerenkov gas over this thin section, it is important that a zero temperature coefficient material is used. CER-VIT, a zero temperature coefficient, very hard ceramic is ideal for this application. The mirror should be pitch-polished free of pits (coronograph quality) to enhance the ultraviolet reflectivity. A change of temperature can change the focal length or if the mirror is not uniform as in the thin center section, it will distort. Thus, it is important to hold the counter at or near a fixed temperature. This we have accomplished by controlling the temperature of the counter slightly above ambient with heated water which circulates in a tube wrapped around the entire length of the counter. In addition we have wrapped the entire counter in glass-wool insulation.

2. <u>Light Collecting Mirrors</u>

Light collecting mirrors used in the Cerenkov counters described here are very similar in construction and purpose to those we have fabricated in the past for threshold Cerenkov counters. Here we are attempting only to focus the light onto a face of 5-cm diameter photomultiplier tube. Thus, the resolution of the mirror need not be very high. Such mirrors can be fabricated easily and cheaply. However, the mirror used for the veto phototube has an annulus removed. This annulus is a slight ellipse since the mirror is at a 10° angle relative to the direction of the Cerenkov light. The annulus must be removed with an accuracy of better than 1 mm. Also, we want to have a selection of mirrors so the width and radius of the annulus can be effectively varied. In addition we want to be able to fabricate mirrors on short notice as the experiment dictates.

In order to meet these requirements we have made a large number of mirrors and have learned to cut the annuli out of the mirrors quickly. The mirrors are made of ordinary window glass by slumping them in an oven over a carbon mold machined to the desired shape of the mirror. Once the carbon mold is machined, a large number of mirrors can be made with little effort. It would be desirable to make these mirrors out of lucite in order that the annulus can be easily machined. However, we have found lucite mirrors even though anealed will gradually change their shape over a period of several months making them useless. Thus, glass is a much better material providing the annulus can be removed without too much difficulty.

Figure 8 is a photograph of several of these slumped glass mirrors. The annulus is removed by covering the mirror with a heavy composition material used by gravestone engravers. We remove accurately the area covering the glass that we want removed. This is done by placing the mirror in its mount below a jig holding an Exacto knife. The knife can rotate in a circle of the desired radius. The material removed is an ellipse precisely the correct shape to allow the ring of Cerenkov light to pass through it. After the material is removed we sandblast most of the glass away from both sides and then machine away the remaining glass with a diamond tool. Such a mirror can be made in less than a day. In the center of the counter we remove a section the shape of the beam spot to allow the beam particles to pass unaffected. We cover this portion with aluminized mylar. The mirrors in Fig. 8 have a cross mark in the center used for alignment studies. For the 10-meter counter we made 30 blank mirrors and 15 mounting frames. Each frame is coded with a binary code that can be sensed by micro-switches inside the counter allowing one to tell remotely which mirror is in position. Table II gives a summary of the mirrors we have made for use with both counters. Our ability to fabricate these mirrors has been crucial to operations of the Cerenkov counters. In actual practice one mirror is used for almost all measurements so that the mirror is seldom changed. Figure 9 shows the image of a point source placed at the center of curvature of one of the light collecting mirrors. The diameter of the image is less than one centimeter. The diameter of the image of parallel light from infinity such as Cerenkov light would be one-half of this. Thus, the quality is more than adequate for our needs as a light collecting mirror.

Figure 10 shows the result of a computer ray tracing of the Cerenkov light emitted by a particle at 10 mrad through the optics of the 10-meter Cerenkov counter up to the face of a phototube placed at the focus of the light collecting mirror. Two side views of the phototube face is given in the display. One sees in Fig. 10a where the angle of the mirror is 15^{o}, the spot is well inside the diameter of the phototube. One sees the astigmatic image due to the tilt of the mirror. Also the blur due to the imperfections of the mirror as shown in Fig. 9 are acceptable. Fig. 10a-10e the tilt angle of the mirror is increased showing the effect of off axis astigmatism. From these results we see the importance of keeping the angle of the mirror small to maintain good optics. In both counters described here the tilt angle of the mirror was 10°.

Windows

Two types of windows are used in the counters described here: Quartz and mylar.

The quartz windows are made of a fused synthetic silica, Suprasil 2, manufactured by Amersil Inc. The ultraviolet transmission of Suprasil 2 extends considerably beyond that of natural quartz with a 50% transmission point of 1700 Å.

The mylar windows must be able to flex in and out because the counters are designed to operate above and below one atmosphere. The windows must withstand the maximum operations pressure 75 PSIA and the windows should be as thin as possible. We tested 0.018, 0.025 and 0.035 cm mylar to destruction by repeatably flexing them every four seconds to 80 PSIA. We found the windows failed after 4200, 7200, and 18400 flexures respectively. At this cycle rate the windows got quite warm. We chose to make the windows of 0.025 cm thick mylar covering them with .0025 cm aluminum to make them light tight.

Pressure and Temperature Readouts

We have supplied the counters with both a Borden gauge made by Wallace and Tierman and a Digigauge made by Ashchroft. Both gauges read 100 PSIA full scale. The Borden gauge has no electronic parts and is considered the standard for each counter. We have located the Borden gauges on the counters. We use the Digigauge as a remote pressure readout because of the ease with which it can be read into the computer. It has slightly better accuracy than the Borden gauge but is less reliable. From our discussion in Section II we saw that we need an accuracy in in the pressure readout of about 1%. However, this is 1% of the operating pressure, which is usually about one atmosphere. This corresponds to 0.15% of the full scale reading. From Table I we see both gauges are considerably better than this. The temperature is read by a platinum resistance thermometer inserted into the Cerenkov gas. The device is manufactured by the Weed Instrument Company and has a resolution of 0.1°F, which is considerably better than that required as discussed in Section II. The temperature is remotely recorded and is read by the computer.

Baffling

The counters are anodized black everywhere inside to absorb stray light. A baffling ring is inserted every 0.6 meter, which eliminates light that may be reflected from the walls of the pressure vessels.

Phototubes

The preferred photomultiplier is the RCA8850M/C31000M, which is a quartz-faced tube. For this tube the values we have obtained for the constant N in the expression

$$N_e = N\theta_c^2(cm)$$

are between 140 to 170. A second choice is the 56 DVVP. For this tube we have obtained values of N of 100 to 140. The 8850 has a gallium arsenide first dynode which has a gain of 40 providing there is approximately 600 volts between the cathode and the first dynode. This high gain of the first dynode allows the tube to resolve single photoelectrons and is quite convenient in setting the high voltage when the tube is used at low light levels as in Cerenkov counters. Here the bias is often set sufficiently low to count single photoelectrons. Both tubes have bialkali photocathodes with quantum efficiencies of typically 35% for the RCA tubes and 25% for the Amperex tubes. The response of the RCA tube extends from 1900 to 5200 Å (50% of peak response). The RCA tubes have low noise. A good tube will have less than 1000 counts per second almost all of which are due to single photoelectrons. We have normally used positive high voltage to avoid breakdown across the quartz window of the photocathode. However, if the front face of the tube does not touch anything that is grounded such as a lucite light pipe, negative high voltage will work. With the tube base diagram shown in Fig. 11 one gets 0.1 volts into 50Ω for the single photoelectron peak at voltages between 2200 to 2700 volts.

Although the noise levels of the RCA8850 phototube is very low, not all tubes meet advertized specifications. RCA also has had failures of their graduated quartz seals allowing air into the tubes. The symptoms are that first the noise level in the tube goes up. When the tube gets gasy, it will resonate due to ion feedback with a time constant of 300 to 400 nsec. It is thus very convenient to keep track of the noise level of tubes in counts per second with a bias set to count a single photoelectron. RCA hopes they have solved the problems relating to the failures of their graduated quartz seals. One has to be careful using these tubes (as any phototube) around helium in that the envelop is pervious to helium. To avoid this problem, we have vented the tubes by circulating air into the enclosure holding the photomultipliers.

Filling Gases and Material in Beam Line

There are three radiating gases that one may consider using at high energies; helium, nitrogen, and hydrogen. Table III gives the properties of these gases pertinent to their use as a Cerenkov radiator. Properties of special interest for each gas are indicated in the Table. Helium is the best choice at high energies because the dispersion, ω, is the smallest (column 4) giving the smallest angular chromatic dispersion. It also has a small gas constant, k, allowing reasonable operating pressures (column 2, Table IV) at high momenta. At low energies the operating pressure for helium becomes very large (see Fig. 2a) and a more refractive gas must be used. Nitrogen is a good choice. The larger dispersion of nitrogen is not a serious handicap since at low energies there is a large separation in Cerenkov angle between particles. Hydrogen has about the same gas constant as nitrogen but is more dispersive. It has a very low mass for the same index of refraction and consequently makes a smaller contribution to the total absorption and radiation length of the counter (see columns 4 and 5 in Table IV). This can also be seen from columns 6 and 7 of Table III. For a given index of refraction the radiation length, Δt, is proportional to $1/kt_0$ and the interaction length, $\Delta\lambda_{ABS}$, is proportional to $1/(k\lambda_{ABS}/\rho)$. Since λ_{ABS} is about the same for all gases, we could simply compare k/ρ. We see from columns 6 and 7 in Table IV that both these quantities are large for hydrogen.

We have listed neon in Table III although helium is superior in energy regard including cost except for one property. Glass is not pervious to neon as it is to helium allowing one to immerse the phototube inside the counter.

Table IV tabulates the material in the beam line due to windows and gas with the counter set at a pressure for π's at an energy of 100 GeV/c. We see the thin section of the mirror, if it is used, dominates the radiation length.

VII. EFFECT OF EXTENDED WAVELENGTH RESPONSE AND THE POSSIBLE USE OF WAVELENGTH SHIFTERS IN CERENKOV COUNTERS AT HIGH ENERGIES

Since the Cerenkov yield is proportional to $1/\lambda$, it is useful to be able to extend the response of the photomultiplier tube into the far ultraviolet to increase the light yield,[6,7,8] the radiating gas must be transparent into this region. Column 8 of Table III gives the approximate wavelength cut-off for the gases of interest. Helium is outstanding in this regard.

There are two ways to make use of this potential light increase. One can use synthetic fused silicon windows with their extended ultraviolet transmission and phototubes with quartz envelopes. A second way is to use a wavelength shifter which absorbs the ultraviolet Cerenkov light and remits it near the region of maximum sensitivity of the phototube. An advantage of the second is that one can avoid the use of quartz-faced phototubes with their expensive graduated seals. Tubes without quartz envelopes are normally on hand in sufficiently large quantity that one can select tubes with the highest quantum efficiency. Since there is a considerable difference between tubes, one can realize a significant gain by selecting an outstanding tube. The manufacturer's measurements on tubes are not useful to make this selection. There seems to be no correlation between tubes with a high quantum efficiency as rated by the manufacturer and tubes that perform well in a Cerenkov counter.

We have considered carefully the two methods and found we were forced to go the route of quartz tubes and windows to obtain the best Cerenkov counter. At high energies the resolution of the counter is limited by the dispersion of the gas, the variation of the index of refraction with wavelength. Thus, if a wider wavelength range is accepted in order to obtain more light we find in order to resolve the Cerenkov light from two particles, one must go to smaller Cerenkov angles as indicated by Eq. (3). We see this effect quantitatively as follows.

We assume the counter is designed for some minimum number of photons, N_γ. We assume the maximum length allowable is fixed by experimental conditions. Eq. (9) gives us the Cerenkov angle we must operate for a given range of λ

$$\theta^2 = \frac{CN_\gamma}{L} \left(\frac{1}{1/\lambda_1 - 1/\lambda_2}\right) , \tag{16}$$

where C is a constant. The index of refraction depends on λ and is closely given by a form $1/\lambda$ so the dispersion for the same range of wavelengths is closely given by

$$\omega = B(1/\lambda_1 - 1/\lambda_2) \quad . \tag{17}$$

The maximum operating momentum is given by (8). Substituting (16) and (17) into (8) the term involving λ cancels and we get

$$p_{max}^2 \simeq \frac{m_2^2 - m_1^2}{BC\ N\ /L} \quad .$$

The gain in light yield due to the extended response is cancelled by the loss in yield by having to go to smaller Cerenkov angle to avoid the angular chromatic dispersion. We see no gain is realized in the maximum operating momentum assuming the wavelength shifter works perfectly.

In actual practice a net loss will be realized. The wavelength shifter has other disadvantages. Because the envelope of the phototube is pervious to helium the phototube cannot be placed inside the counter unless one choses to use neon as the radiating gas. Thus, one is forced to place the wavelength shifter on the inside of the quartz window. Since the wavelength shifter emits light isotropically, a loss will occur due to the increased distance of the photocathode from the wavelength shifter.

The presence of small impurities in the working gas not transmitting in the ultraviolet can lead to strong absorption below 2000 Å. Thus special care must be excercised to insure high purity.[8]

VIII. EXPERIMENTAL RESULTS

The counters described here have been used successfully in a high energy experiment for almost two years and have worked as designed. The importance of the feature of being able to detect and veto unwanted particles with high efficiency in order that minority particles in a beam can be unequivocally detected has only been fully appreciated after use in a physics experiment.

Alignment of the counter and the primary mirror, a primary concern during the design of the counter, was found to be relatively easy to achieve with a particle beam. The critical alignment is between the axis of the beam and the angle of the primary mirror relative to the annulus of the veto mirrors and thus can only be accurately determined with the beam. The coincident rate between the counter and a beam trigger is observed as the angle of the primary mirror is changed. In practice this is a relatively easy measurement to obtain. Figure 12 is the result of such a measurement to determine the horizontal mirror angle. One sees that the curves are sharpened considerably by putting the anti-coincidence photomultiplier tube in veto. Such a curve is obtained in about 15 minutes. Each division corresponds to an angle of 0.05 mrad. For large changes in operating pressure the mirror's alignment curves should be repeated since the pressure vessel will bend slightly with a large change of pressure.

The 10-meter counter has been used in a mass search for long-lived particles of masses up to 4-GeV in an 80-GeV particle beam. The results of this search are shown in Figure 13. These results show the enormous power of Cerenkov counters in identifying particles at high energies. From Fig. 13b we see rejections of 10^8 are obtained.

For the results shown in Fig. 13a the counter was operated with helium as the radiating gas with a Cerenkov angle of 8.5 mrad and with an annulus width of 1.5 mrad. Above 30 PSIA the threshold counter was used to veto π mesons. The horizontal bars imply a measurement where no counts were observed but is plotted at a level as if one count had occurred. Thus, the background near the mass of the antiproton is one part in 10^6 of the incident flux and is limited by statistics in that the background points are no count measurements.

Figure 13b shows the results of the search at high masses obtained using nitrogen in the counters. Below 8 PSIA the differential counter was operated singly at 8.5 mrad with a 2 mrad annulus. Above 8 PSIA the threshold counter was used to veto pions, kaons and antiprotons. Above 8 PSIA the veto mirror was removed entirely from the differential counter allowing one to operate the counter in a broad band mode. In this broad band mode the capability to veto particles with the veto phototube is lost but a big gain is made in range of mass accepted at each pressure setting of the counter allowing the mass search to be made in much coarser steps and with a corresponding increase in counting rate. From the width of the anti-deuteron peak we see this width is about 6 PSIA corresponding to a mass acceptance of several hundred MeV. The background in the region of the mass of the anti-deuteron approaches 1 part in 10^8 and is limited by statistics. Although this was obtained with two counters, each counter employed only one phototube. This is a remarkable result for such a simple system. With the 13-meter counter with its split mirror and added rejection, one would hope to get an added factor of 100 in rejection indicating one should be able to achieve rejection ratios of at least 10^{10}.

Figure 12 is a pressure curve obtained with the 13-meter counter at 100 GeV. This counter was constructed primarily to detect protons and thus, the counter was operated in a larger Cerenkov angle of 10 mrad with an annulus of width 1.2 mrad. The protons are well separated from the pions and kaons, even at this Cerenkov angle we see at 100 GeV we still resolve pions and kaons. A comparison of this pressure curve with the predictions given in Fig. 4d show the counter operates as predicted by the curves. To resolve pions and kaons at greater energies, one should operate at a smaller Cerenkov angle and add the pulses from the two phototubes if necessary.

IX. CONCLUSIONS

The design considerations necessary for the fabrication of a differential Cerenkov counter for use at FNAL energies have been reviewed and their practical implications given. At high energies these considerations force one to operate with a gas of low dispersion such as helium. Also, these considerations compel one to operate at as small a Cerenkov angle as possible consistent with obtaining sufficient light intensity. Small Cerenkov angles are found to offer numerous simplifications and increase the maximum operating momentum. The cost savings from these simplifications more than offset the increased cost of the additional length. We have described two counters that were designed with these principles. The counters are now in use and we have found their operation completely predictable. We have stressed the design feature of being able to count with high efficiency unwanted particles so that they can be rejected. Without this feature the counter is of limited use as a beam line counter in beams of high intensity.

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TABLE I

CHARACTERISTICS OF COUNTERS

	10-Meter Counter	13-Meter Counter
Primary Mirror		
f	971.5 cm	1298 cm
Diameter	30.5 cm	33.0 cm
Thickness	5.1 cm	5.1 cm
Material	CER-VIT	CER-VIT
Size of Hole	6.35 cm x 6.35 cm	5.1 cm Dia
Size of Thin Section	8.9 cm	-
Thickness of Thin Section	0.25 cm	-
Secondary Mirrors		
f	58.4 cm	58.4 cm
Diameter	30.5 cm	34.3 cm
Thickness	0.63 cm	0.63 cm
Material	Glass	Glass
Size of Thin Section	6.5 cm Square	5.7 cm Dia
Thickness Thin Section-Material	.001 cm Mylar	.001 cm Mylar
Number Veto Mirror Positions	6	1
Split Coincidence Mirrors	No	Yes
Quartz Windows		
Diameter	5.40 cm	5.40 cm
Thickness	0.95 cm	0.95 cm
Material	Suprasil 2	Suprasil 2
Pressure Rating	105 PSIA	105 PSIA
Beam Windows		
Diameter	8.9 cm	8.9 cm
Thickness-Material	.025 cm Mylar (+.0025 cm)	.025 cm Mylar (+.0025 cm)
Phototubes		
Type (preferred)	RCA C31000M	RCA C31000M
Number Coincidence Tubes	1	2
Number Veto Tubes	1	1
Gas		
High Momenta	Helium	Helium
Low Momenta	Nitrogen	Nitrogen
Pressure Vessel		
Material	Aluminum	Aluminum
Diameter (I.D.)	38.1 cm	38.1 cm
Diameter (O.D.)	40.6 cm	40.6 cm
Insulating Material	Glass Wool	Glass Wool
Maximum Operating Pressure	75 PSIA	75 PSIA
Total Length	11.48 meters	13.9 meters

TABLE I

CHARACTERISTICS OF COUNTERS
(continued)

	10-Meter Counter	13-Meter Counter
Pressure Readout		
Local	Borden Gauge	Borden Gauge
Full Scale Reading	100 PSIA	100 PSIA
Accuracy	.066%	.066%
Repeatability	.03%	.03%
Remote	Digigauge	Digigauge
Full Scale Reading	100 PSIA	100 PSIA
Accuracy	.05%	.05%
Repeatability	.02%	.02%
Temperature Readout		
Type	Platinum Resistance	Platinum Resistance
Resolution	.01°F	.01°F
Cerenkov Angle		
Pions-Kaons	7-8.5 mrad	7-8.5 mrad
Protons	7-10 mrad	7-10 mrad
Maximum Cerenkov Angle	15 mrad	13 mrad

TABLE II

DIMENSIONS OF ANNULI OF MIRRORS NOW FABRICATED

Counter	Mirrors	θ	θ
10 Meter	1	8.5 mrad	1.0 mrad
	2	8.5	1.5
	3	8.5	2.0
13 Meter	1	10.0	1.2
	2	8.5	1.2
	3	8.5	0.6
	4	8.5	0.3
	5	7.0	0.6
	6	7.0	0.3

TABLE III

PROPERTIES OF He, Ne, N_2, AND H_2 RELEVANT TO USE AS CERENKOV RADIATOR AT HIGH ENERGIES. PARTICULARLY USEFUL PROPERTIES ARE INDICATED.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GAS	$\rho(300^\circ C)$ (gm/cm^3)	$t_0(300^\circ C)$ (meters)	$k(300^\circ C)^*$ (atm^{-1})	ω(1900-5200Å) (%)	λ_{ABS} (gm/cm^2)	kt_0 $(atm^{-1}cm)$	$\lambda_{ABS}k/\rho$ $(atm^{-1}cm)$	λ(50%) (Å)
He	0.000162	5804	$\boxed{3.221 \times 10^{-5}}$	$\boxed{4.5}$	59.7	18.70	11.90	600
Ne	0.000817	354	6.170×10^{-5}	4.8	77.7	2.18	5.87	~1200
N_2	0.001138	333	$\boxed{2.816 \times 10^{-4}}$	12.0	80.3	9.38	19.80	~1100
H_2	$\boxed{0.0000821}$	7681	1.329×10^{-4}	16.5	55.9	$\boxed{102.00}$	$\boxed{90.60}$	~1700

*Evaluated at 3342 Å.

TABLE IV

MATERIAL IN BEAM LINE ASSUMING PRESSURE IS SET FOR PIONS AT 100 GEV.

Material	(1) Length (cm)	(2) Pressure (PSIA)	(3) Mass (gm/cm^2)	(4) Δt (%)	(5) $\Delta\lambda_{ABS}$ (%)
Helium	1000	18	0.198	0.230	0.330
Nitrogen	1000	2	0.155	0.410	0.190
Hydrogen	1000	4	0.022	0.035	0.039
Mylar	0.050		0.071	0.170	0.091
Aluminum	0.005		0.014	0.057	0.014
CER-VIT (Optional)	0.254		0.635	2.350	0.640

FIGURES

Fig. 1 Conceptual design for the differential Cerenkov counters described in this article.

Fig. 2 (a) This operating pressure for pions, kaons and protons for 8.5 milliradians and helium gas. (b), (c), and (d) give the spread of Cerenkov angles for all three particles with the counter set to count one particle. The curves assume a spread of angles due to the angles of the beam of $\Delta\theta_B$ = 0.125 mrad.

Fig. 3 Same as Fig. 2 with nitrogen as the filling gas.

Fig. 4 Same as Fig. 2 except for a Cerenkov angle of 10 milliradians.

Fig. 5 The 10-meter counter. The insert shows a sectional view of the mirror wheel, which allows veto mirrors with different annulli to be remotely moved into position.

Fig. 6 The 13-meter counter. This counter has a split coincidence mirror reflecting light onto two separate phototubes allowing one to add the pulses or to put them in coincidence.

Fig. 7 Efficiency for 1-fold and 2-fold coincidences versus the number of photoelectrons assuming 100% efficiency for one photoelectron.

Fig. 8 Photograph of several light collecting mirrors with annulus removed.

Fig. 9 Image of a point source placed at the center of curvature of a light collecting mirror. This is an overestimate since light coming from infinity such as Cerenkov light will make a spot one-half of that obtained by a point source placed at the radius of curvature.

Fig. 10 Result of a computer ray tracing through the 10-meter counter to phototube assuming perfect mirrors for a Cerenkov angle of 10 milliradians for various tilt angles of the light collecting mirrors. (a) corresponds to a tilt angle of 15°, (b) 22.5°, (c) 30°, (d) 35°, and (e) 45°. For a tilt angle of 15° the spot of light is small compared to the 5-cm diameter of the phototube.

Fig. 11 Tube base diagram used with the RCA 31000M photomultiplier tubes.

Fig. 12 Coincidence rate of the Cerenkov counter with the beam counter versus the tilt of the primary mirror. A much sharper curve is obtained by requiring no pulse occur in the veto photomultiplier tube.

Fig. 13 Result of the mass search at 80 GeV for (a) low masses using helium as the radiating gas and (b) high masses using nitrogen as the radiating gas.

Fig. 14 Pressure curve obtained with the 13-meter counter at 100 GeV with a Cerenkov angle of 10 milliradians. Comparison with Fig. 4 show the counter acts closely as predicted.

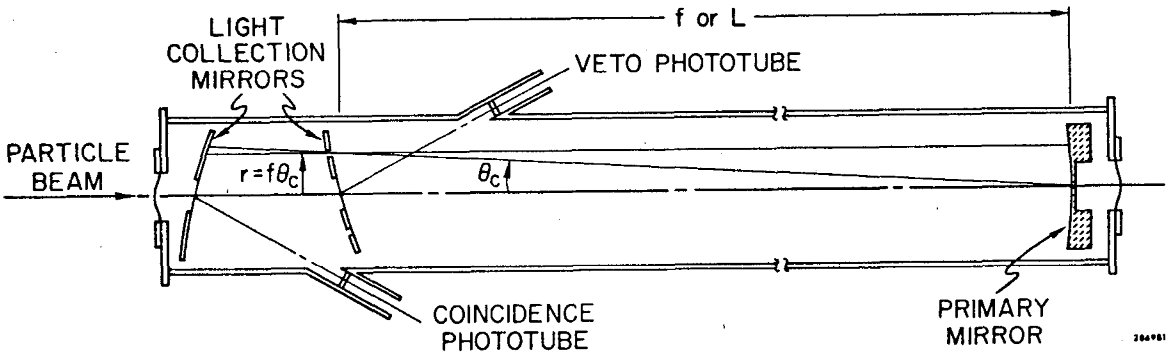

LIGHT COLLECTION MIRRORS
f or L
VETO PHOTOTUBE
PARTICLE BEAM
r = fθc
θc
COINCIDENCE PHOTOTUBE
PRIMARY MIRROR

Figure 1

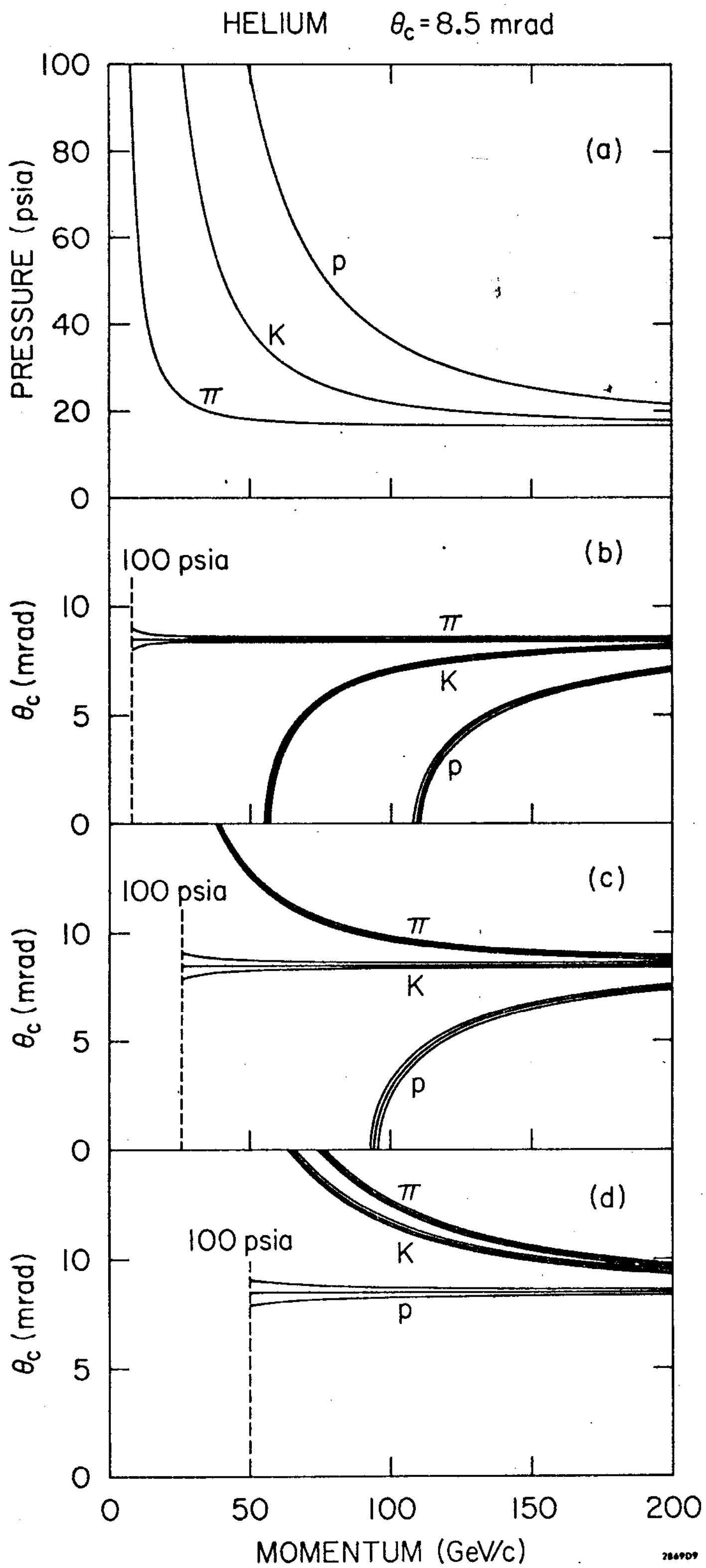
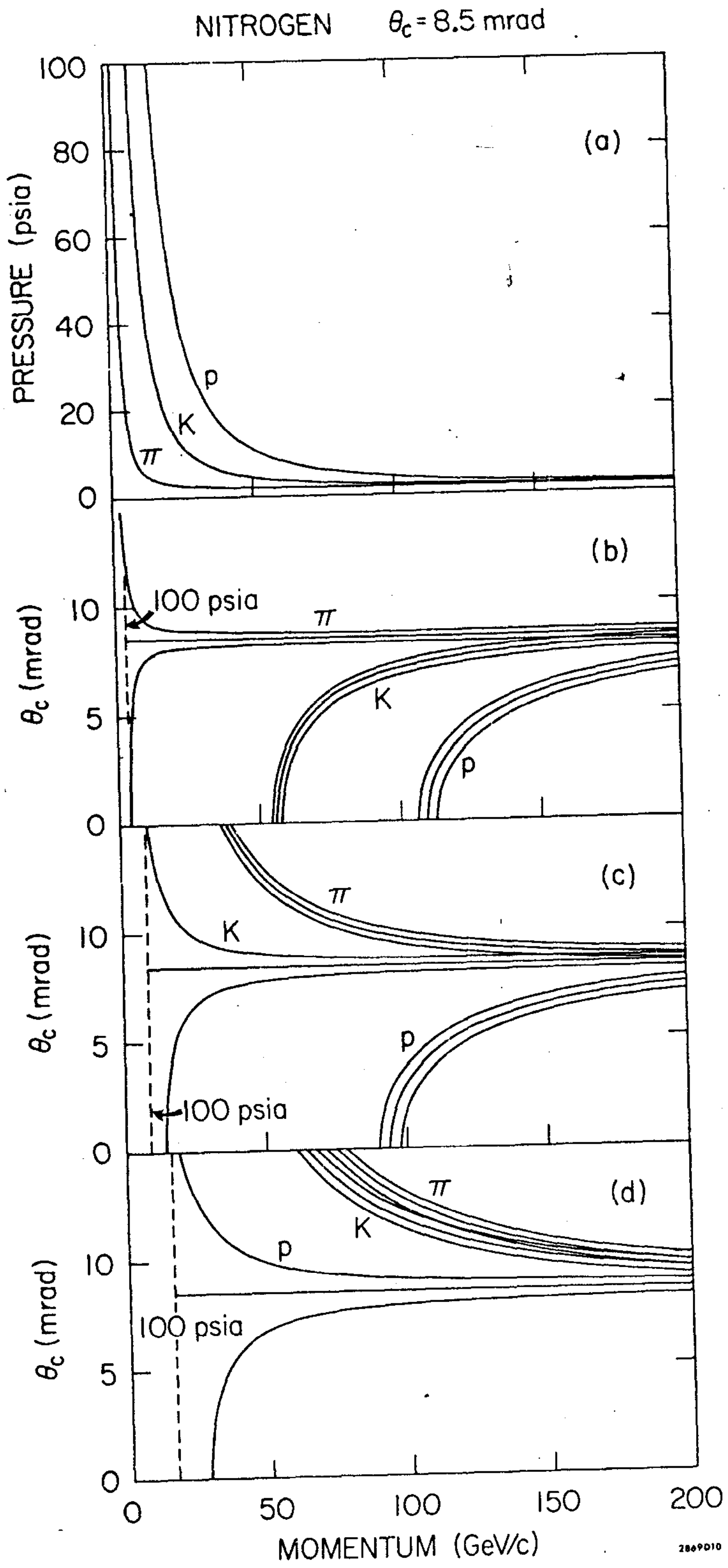
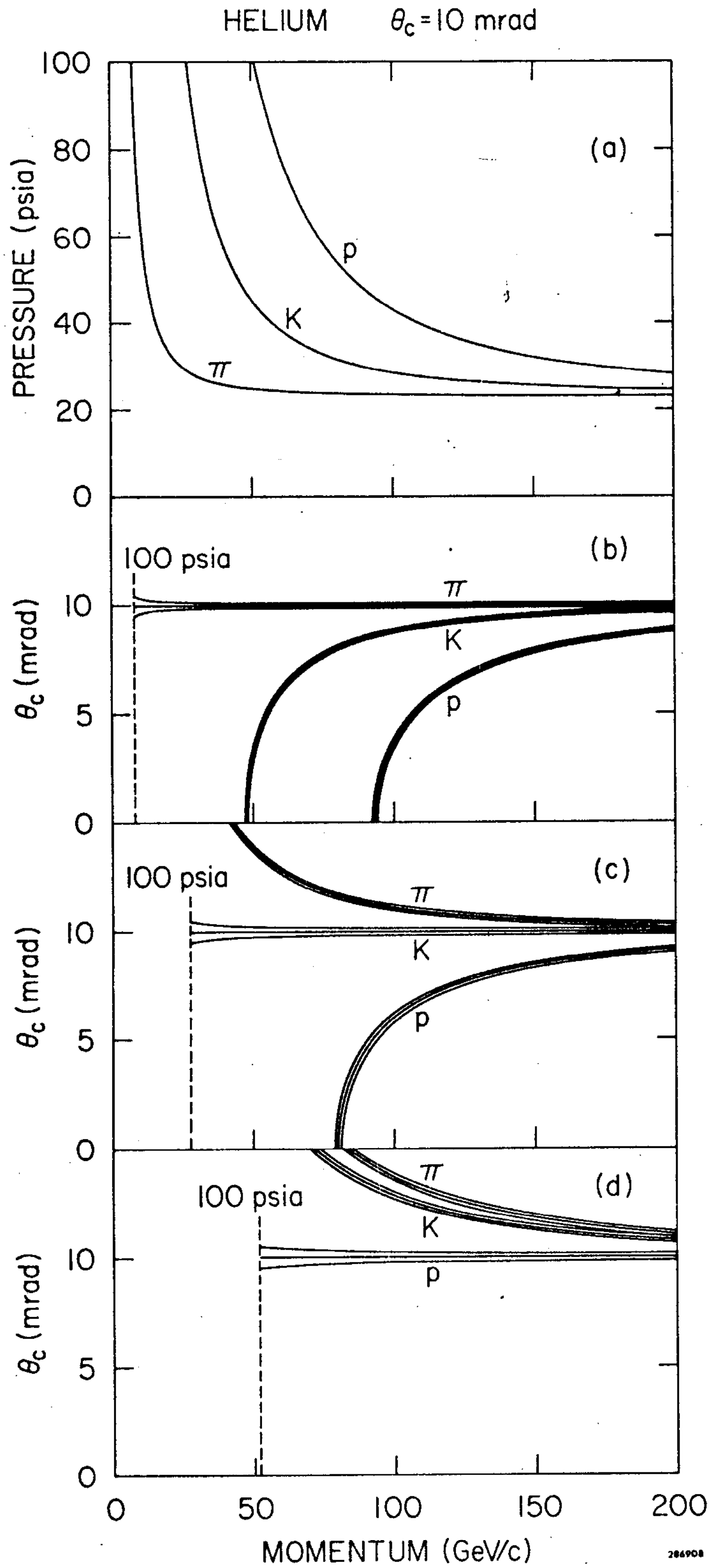

HELIUM θ_c = 8.5 mrad
PRESSURE (psia)
100
80
60
40
20
0
(a)
p
K
π
(b)
100 psia
θ_c (mrad)
10
5
0
π
K
p
(c)
100 psia
π
K
p
(d)
100 psia
π
K
p
0
50
100
150
200
MOMENTUM (GeV/c)

Figure 2



NITROGEN θ_c = 8.5 mrad
100
80
60
40
20
0
PRESSURE (psia)
(a)
p
K
π
(b)
10
5
0
θ_c (mrad)
100 psia
π
K
p
(c)
10
5
0
θ_c (mrad)
π
K
p
100 psia
(d)
10
5
0
θ_c (mrad)
π
K
p
100 psia
0
50
100
150
200
MOMENTUM (GeV/c)
2869D10

Figure 3



HELIUM θ_c=10 mrad
PRESSURE (psia)
(a)
p
K
π
(b)
100 psia
π
K
p
θ_c (mrad)
(c)
100 psia
π
K
p
θ_c (mrad)
(d)
100 psia
π
K
p
θ_c (mrad)
0
50
100
150
200
MOMENTUM (GeV/c)

Figure 4

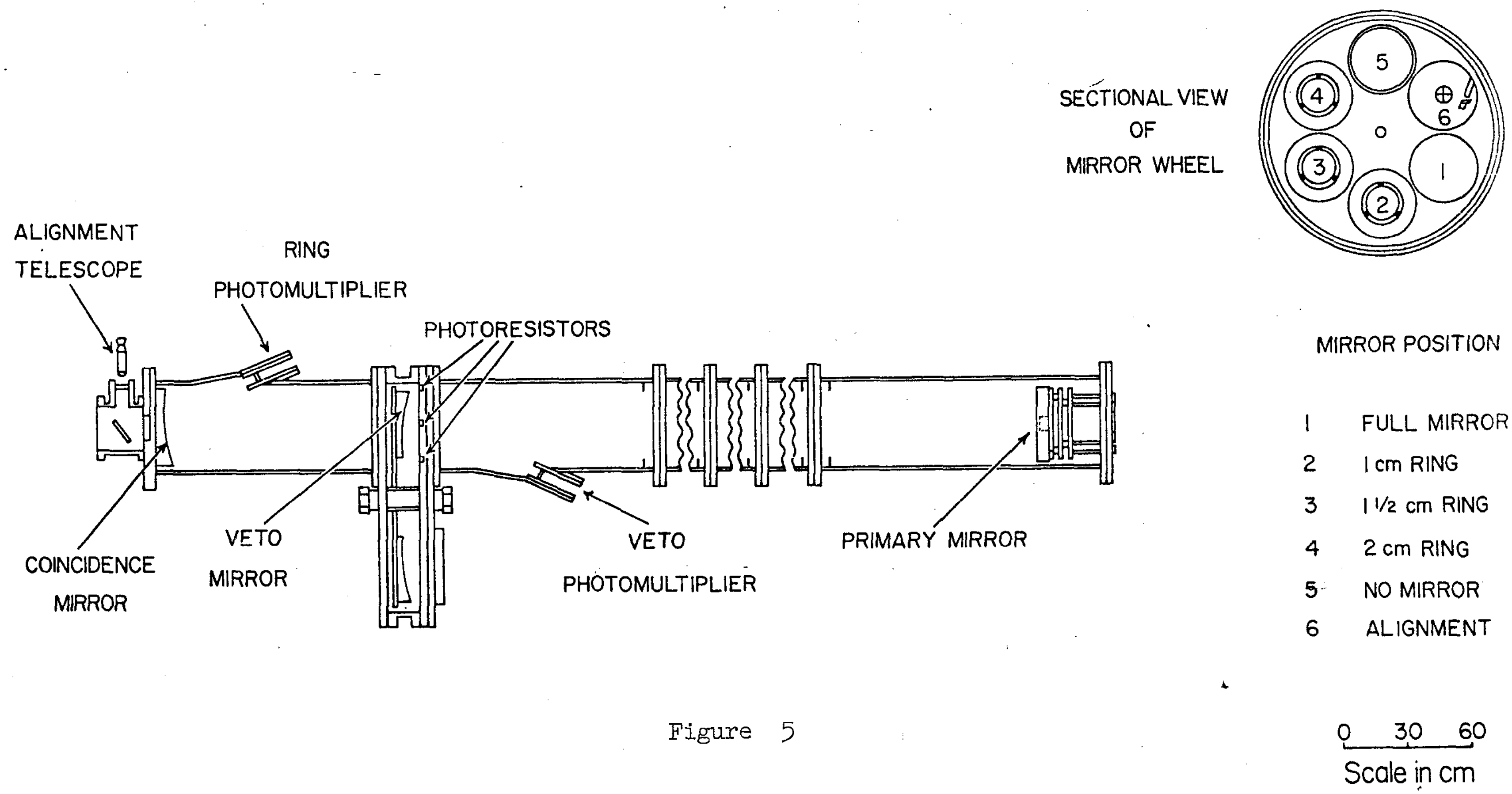

SECTIONAL VIEW
OF
MIRROR WHEEL
5
4
6
3
1
2
ALIGNMENT
TELESCOPE
RING
PHOTOMULTIPLIER
PHOTORESISTORS
COINCIDENCE
MIRROR
VETO
MIRROR
VETO
PHOTOMULTIPLIER
PRIMARY MIRROR
MIRROR POSITION
1 FULL MIRROR
2 1 cm RING
3 1 1/2 cm RING
4 2 cm RING
5 NO MIRROR
6 ALIGNMENT
0 30 60
Scale in cm

Figure 5

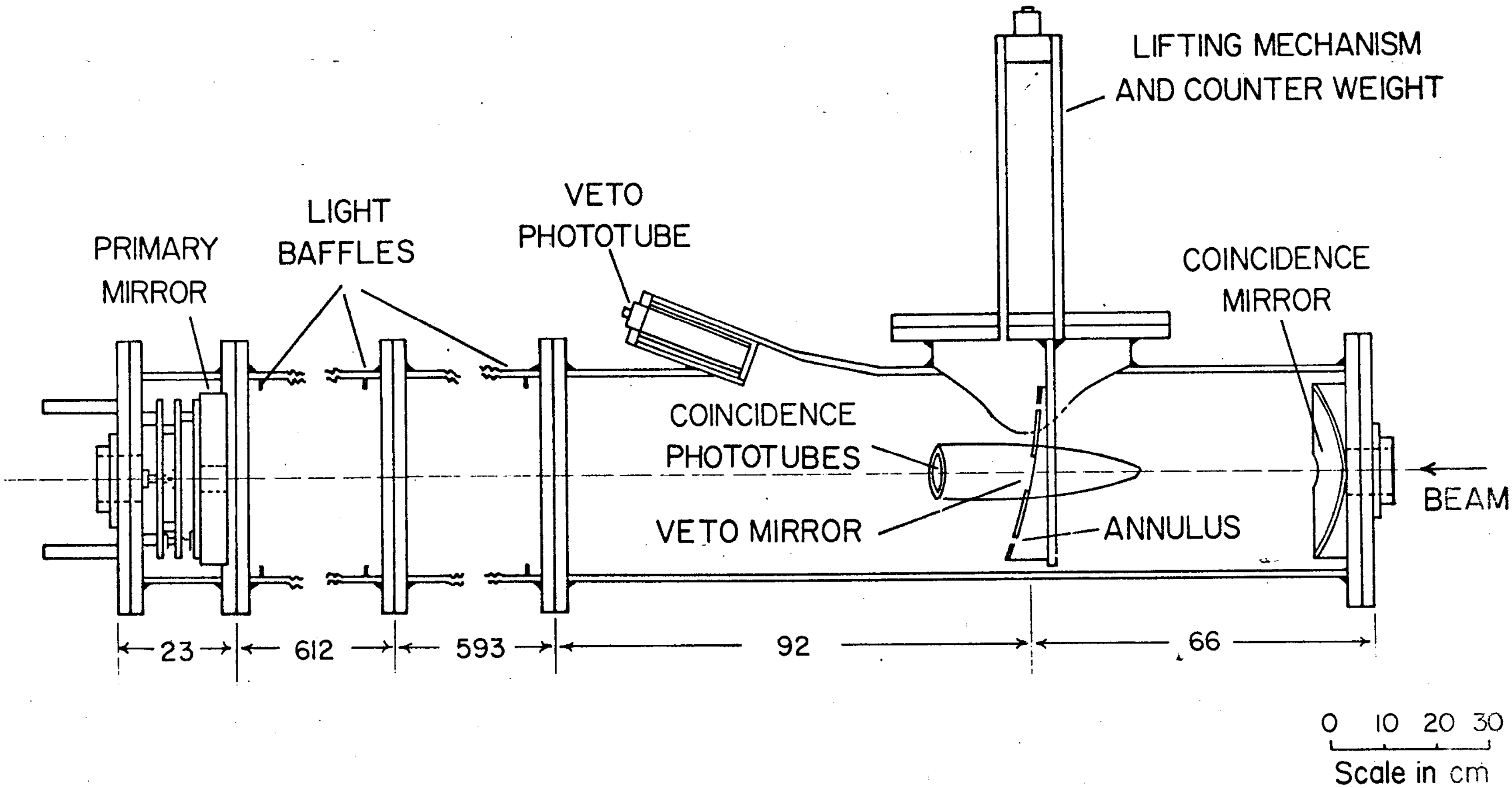
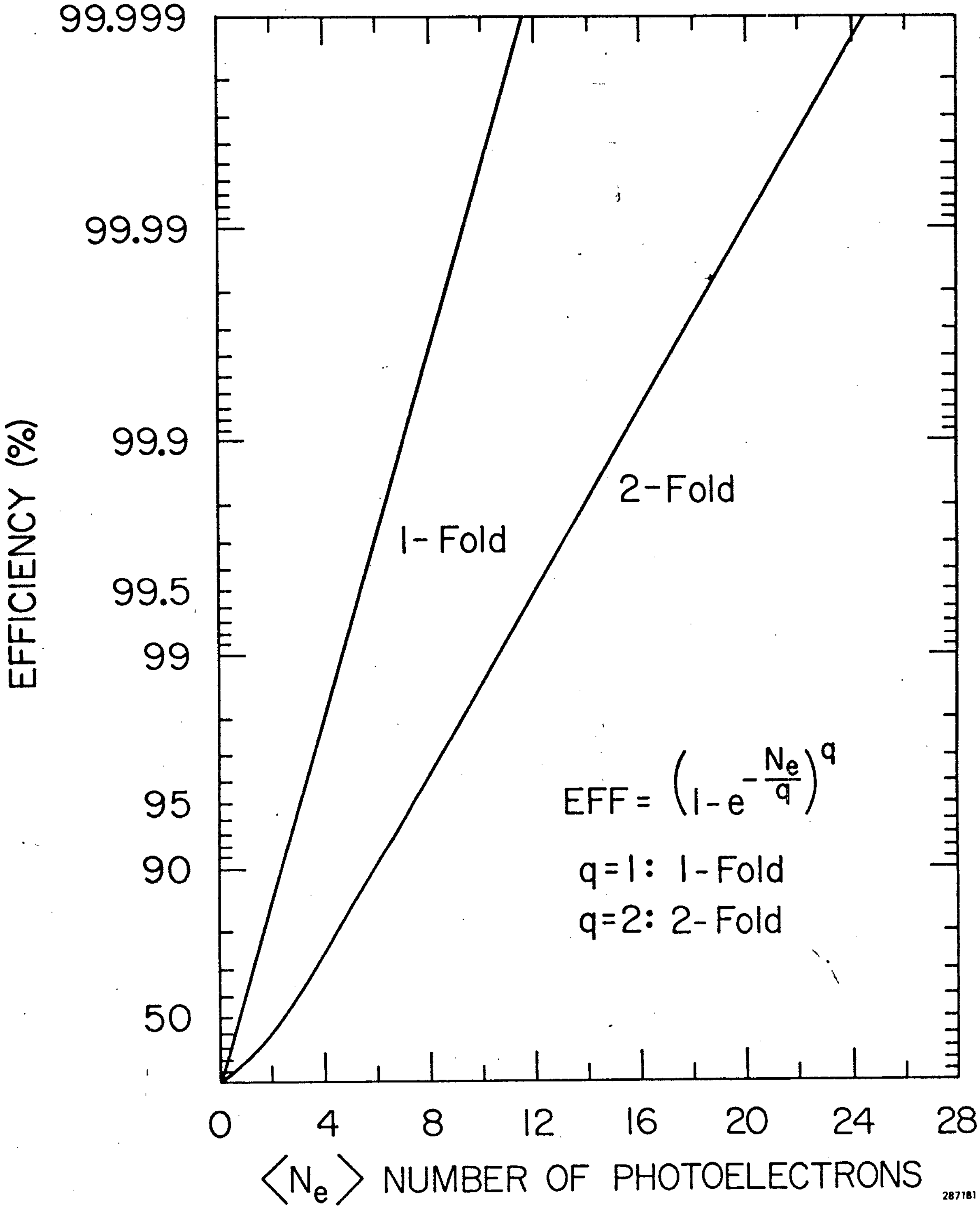


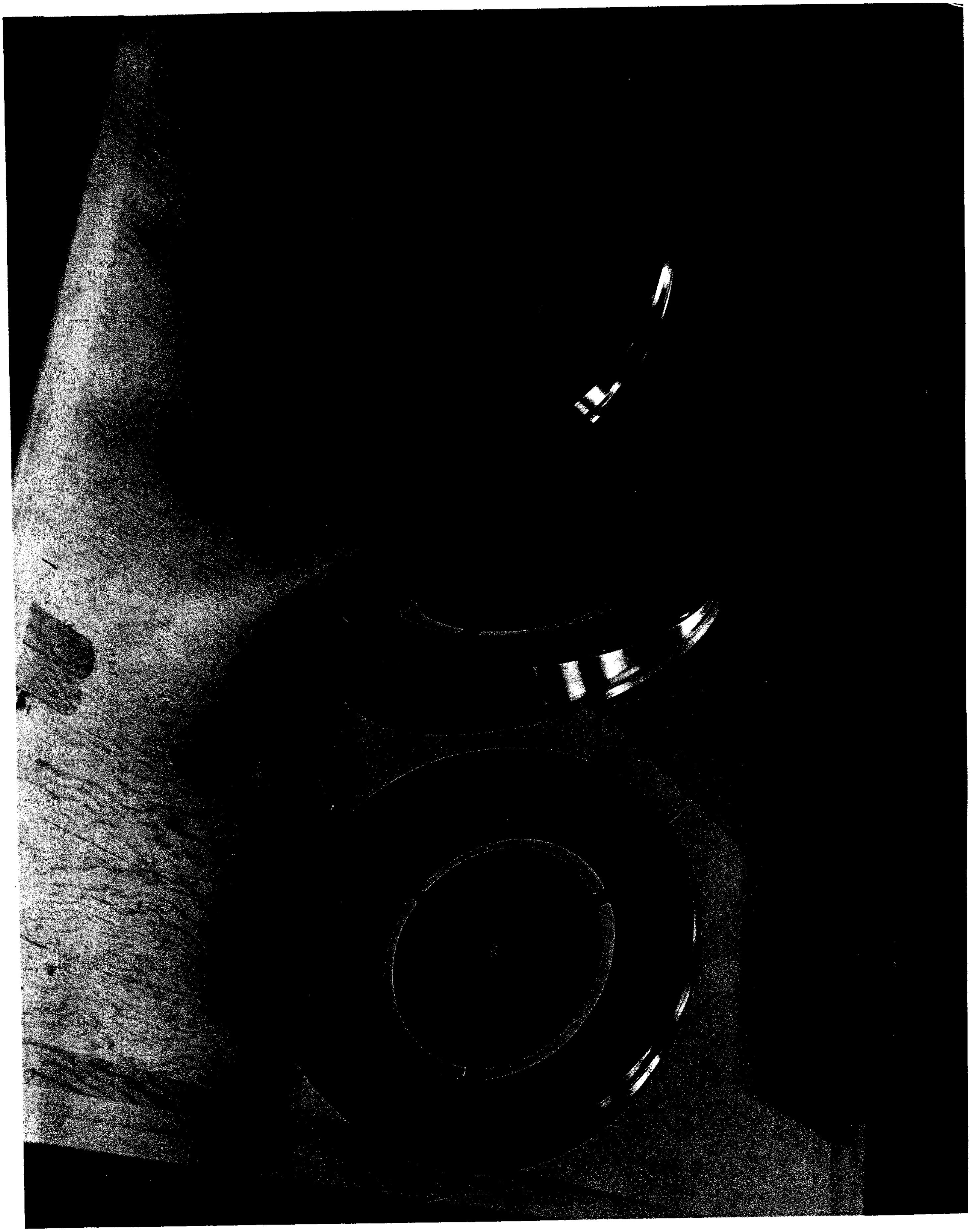
Figure 6

25-74-MB



99.999
99.99
99.9
99.5
99
95
90
50
EFFICIENCY (%)
1- Fold
2-Fold
EFF = $\left(1-e^{-\frac{N_e}{q}}\right)^q$
q=1: 1-Fold
q=2: 2-Fold
0
4
8
12
16
20
24
28
$\langle N_e \rangle$ NUMBER OF PHOTOELECTRONS
287181

Figure 7



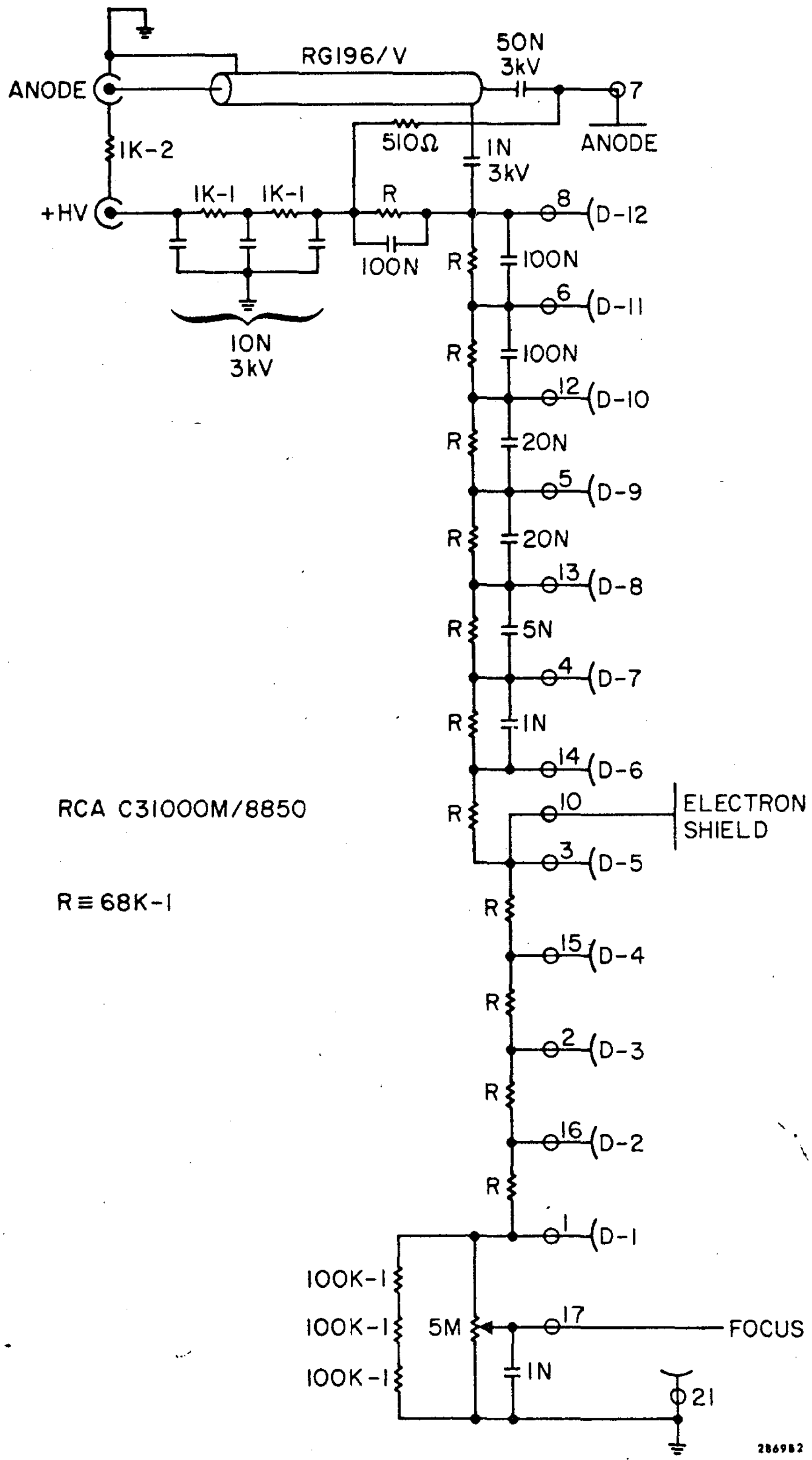

RG196/V
50N
3kV
7
ANODE
ANODE
1K-2
510Ω
1N
3kV
+HV
1K-1
1K-1
R
100N
10N
3kV
8
(D-12
100N
6
(D-11
100N
12
(D-10
20N
5
(D-9
20N
13
(D-8
5N
4
(D-7
1N
14
(D-6
10
ELECTRON
SHIELD
3
(D-5
RCA C31000M/8850
R ≡ 68K-1
15
(D-4
2
(D-3
16
(D-2
1
(D-1
100K-1
100K-1
100K-1
5M
17
FOCUS
1N
21
286982

Figure 11

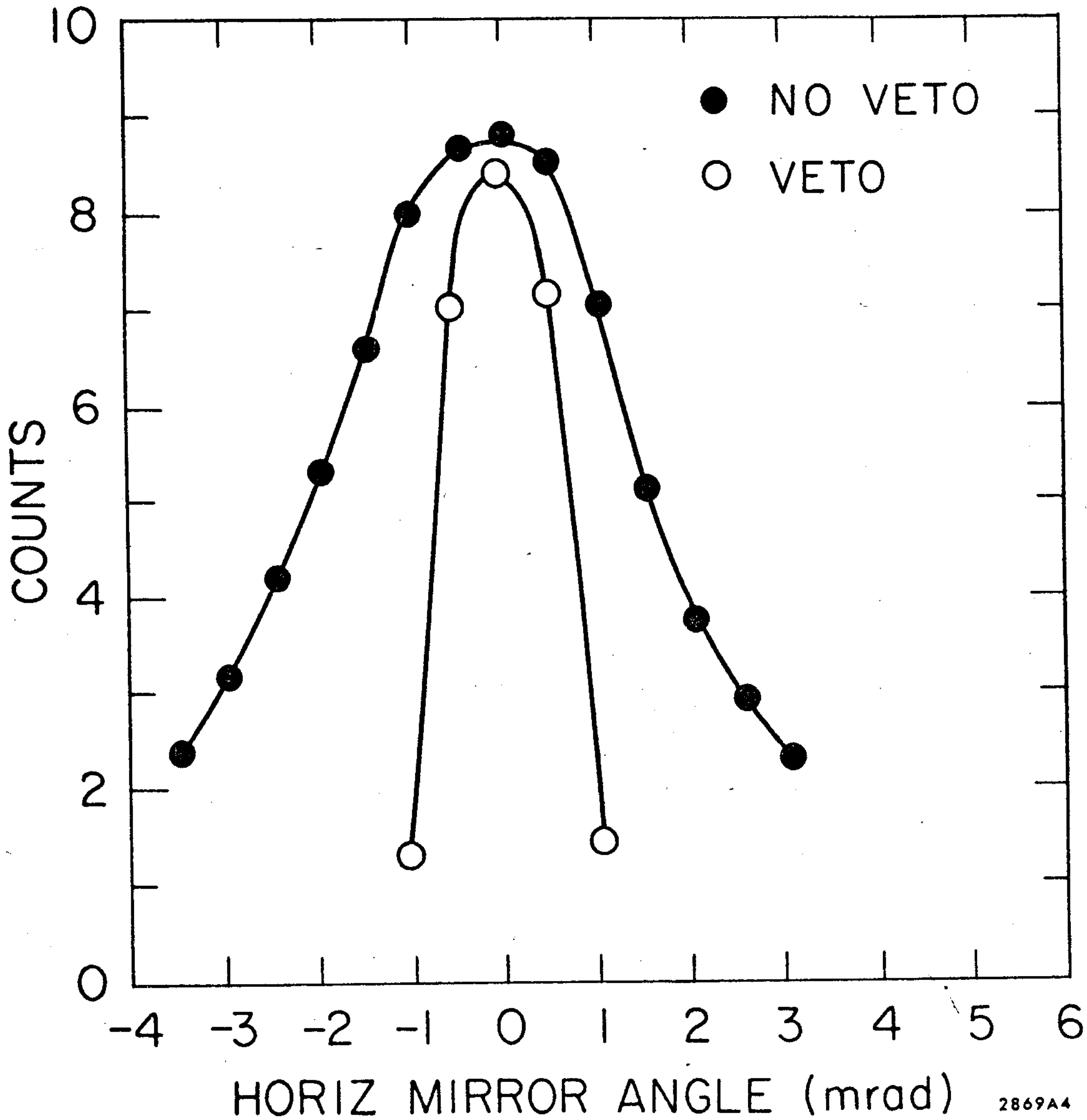
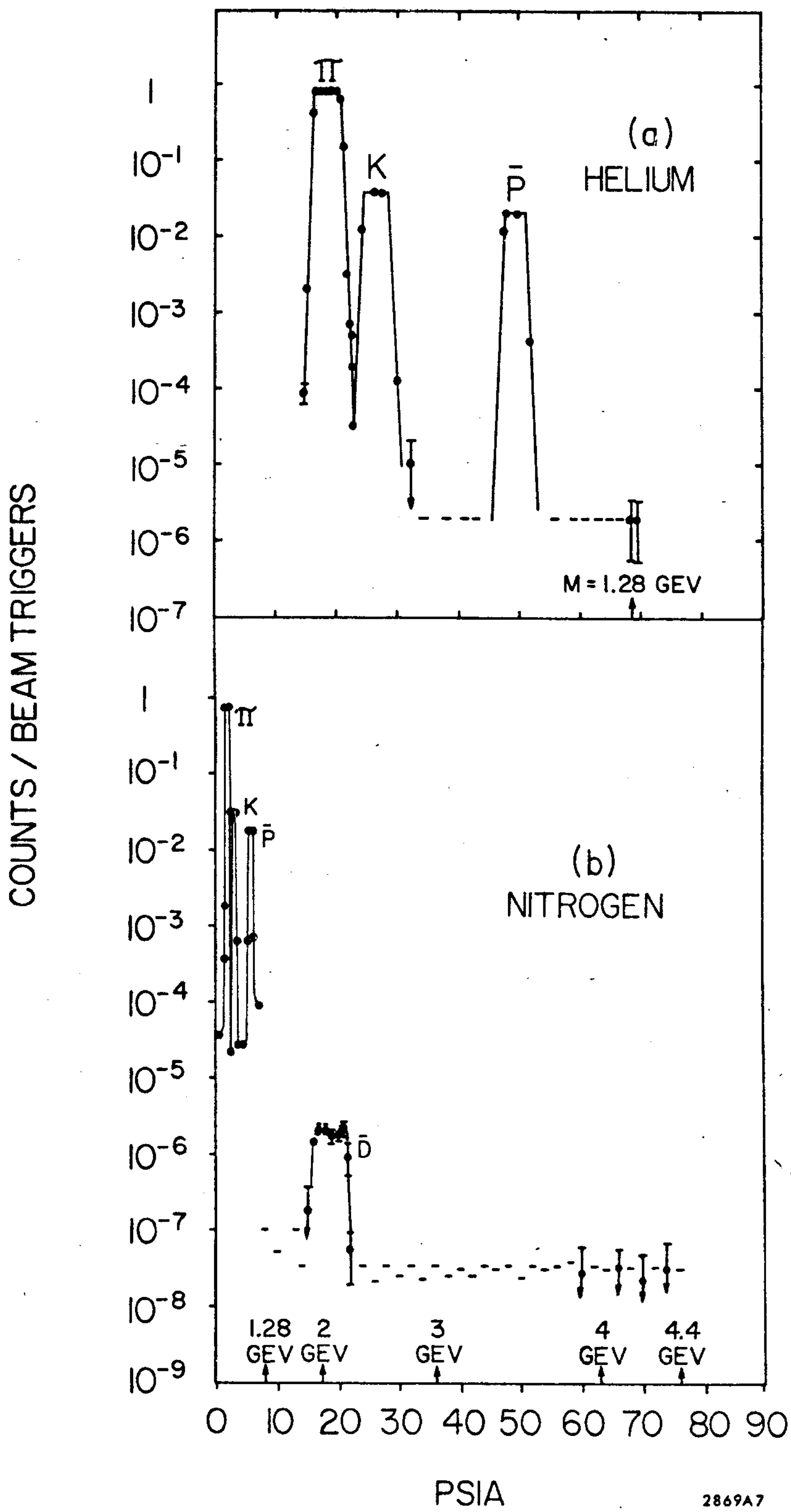
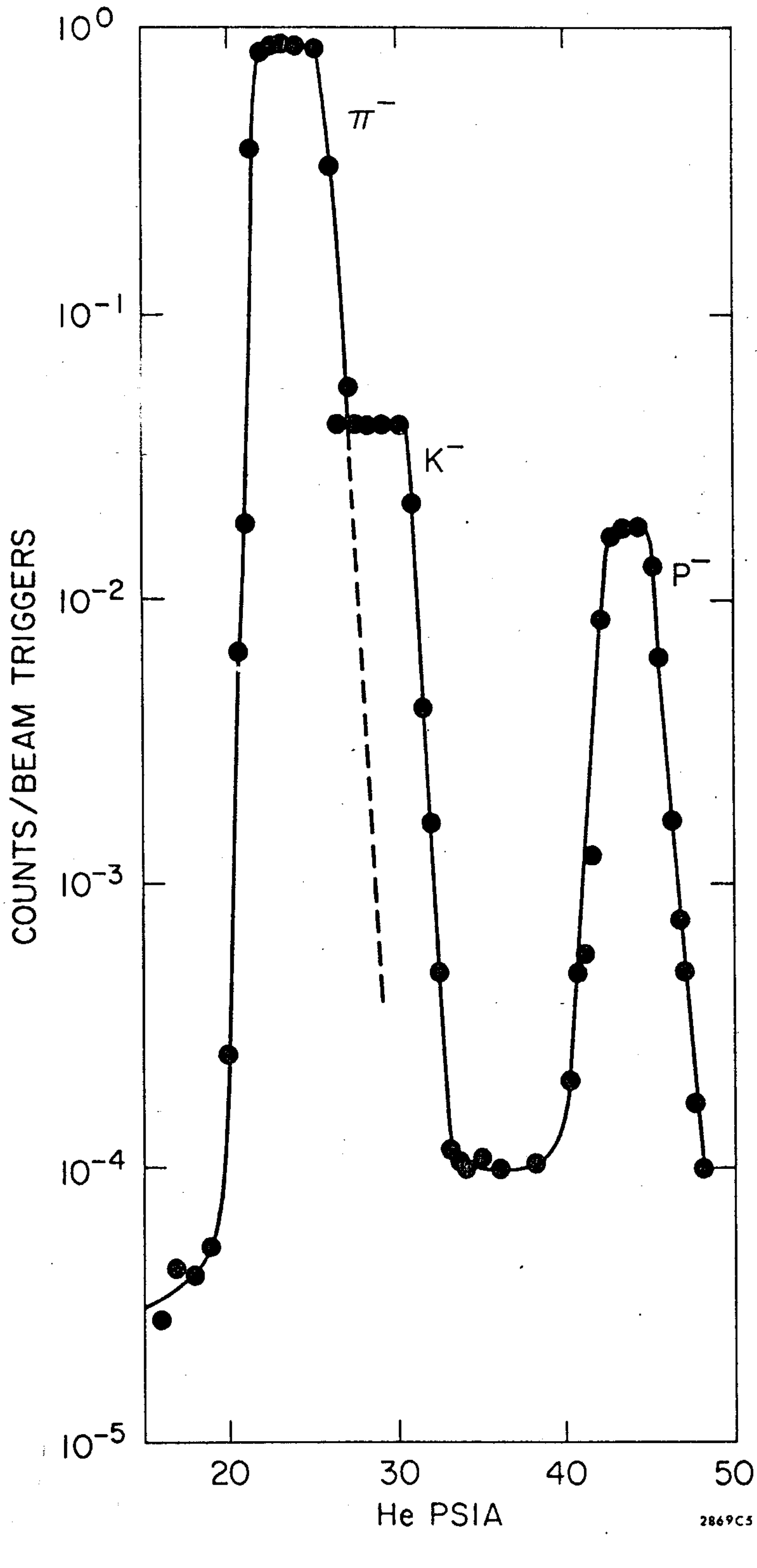


Figure 12



(a)
HELIUM
π
K
$\bar{P}$
M = 1.28 GEV
(b)
NITROGEN
$\bar{D}$
1.28 GEV
2 GEV
3 GEV
4 GEV
4.4 GEV
COUNTS / BEAM TRIGGERS
PSIA
0 10 20 30 40 50 60 70 80 90
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2869A7

Figure 13



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
COUNTS/BEAM TRIGGERS
π^-
K^-
P^-
20
30
40
50
He PSIA
2869C5

Figure 14