DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 67/10
April 1967

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A MAGNETIC SPECTROMETER FOR HIGH ENERGY ELECTRON SCATTERING EXPERIMENTS

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ABSTRACT

A spectrometer composed of deflecting magnets and magnetic quadrupoles is described which is designed to analyze particles scattered in the angular range 8° - 35° and at incident energies up to 6 GeV. A momentum discrimination between 0.2% and 0.7%, depending on the scattering angle, has been achieved. The performance of the spectrometer for the scattering of 5.275 GeV electrons from protons at 12.5° is described.

1. INTRODUCTION

A general electron-proton scattering reaction can be expressed by

$$e + p \rightarrow e + X$$

where X denotes the recoiling system. The momentum of the scattered electron in the centre-of-mass reference frame depends on the nature of the reaction but is independent of the production angle. However, in the laboratory frame the scattered momentum is given by

$$p(\theta, M^*, E) = \frac{E - (M^{*2} - M^2)/2M}{1 + (2E/M)\sin^2 \frac{1}{2}\theta} \qquad (1)$$

due to the motion of the centre-of-mass. In this expression θ is the scattering angle, E is the incident energy, M is the mass of the target particle and M^* is the mass of the system X, the so-called "missing-mass". Typical $p(\theta, M^*, E)$ curves are shown in fig.1 for a fixed E. Experimentally, processes corresponding to different values of M^* are distinguished by using a spectrometer to determine the momentum and production angle of the scattered electron.

For a given incident energy, the momentum of an electron accepted by the spectrometer is

$$p(\theta_o + \delta\theta, M^*_o + \delta M) = p(\theta_o, M^*_o) + \delta\theta \frac{\partial p}{\partial \theta}\bigg|_{\theta_o, M^*_o} + \delta M^* \frac{\partial p}{\partial M^*}\bigg|_{\theta_o, M^*_o}$$

where θ_o and $p(\theta_o, M^*_o) = p_o$ are, respectively, the angular and momentum settings of the spectrometer. Putting $\delta M^* \partial p/\partial M^*|_{\theta_o, M^*_o} = \delta p$ and $\partial p/\partial\theta|_{\theta_o, M^*_o} = p_o G$, we have

$$p = p_o(1 + G\delta\theta + \delta p/p_o). \qquad (2)$$

In this expression G is the slope of $p(\theta, M^*, E)$ for constant M^* evaluated at $\theta = \theta_o$ and $\delta p/p_o$ is the fractional momentum difference between reactions having a missing-mass difference δM^*. If the spectrometer has an angular acceptance $2\Delta\theta$, the range of momenta accepted for a fixed M^* is $2\Delta\theta G$. This "line broadening" due to the finite angular acceptance can seriously limit the useful aperture of a spectrometer unless special precautions are taken.*) For example, at 6 GeV the momentum difference between the elastic scattering reaction and the threshold for single pion production is 2.25% but it is desirable to have a line width considerably better than this. At the same primary energy and at forward angles G is about 1 to 2 radian^{-1}. If we require that $2\Delta\theta G$ be of the order of 0.2%, then the spectrometer acceptance would be limited to between 2 and 4 milliradians which is too small to obtain reasonable counting rates.

To increase the useful angular acceptance, the spectrometer to be described has a sloped acceptance "window" in the $(p-\theta)$-plane such that particles which lie on a sloping straight line in this plot pass through a single point in the horizontal image plane. By adjusting the slope of the acceptance window to match that of the reaction being studied, maximum selectivity is achieved for the desired particles. For a given primary energy, each point in the image plane corresponds to a different value of the missing-mass. In high energy physics such spectrometers are called "sloped-window" spectrometers[2)] but the principle is identical to that used in "Q-focussing" spectrometers[3)] designed for studying nuclear transmutations.

2. DESIGN OF THE SPECTROMETER

2.1 The Sloped Acceptance Window

The essential properties of the spectrometer are illustrated by the particle trajectories shown in fig.2. In contrast with instruments designed for the detection of particles of lower energy[4)5)], separate elements (magnetic quadrupoles and rectangular bending magnets)

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*) This problem has been solved at SLAC by deflecting the spectrometer beam vertically so that the scattered momentum and angle are determined in orthogonal planes. See for example W.K.H.Panofsky, ref. 1).

are used to provide focussing and momentum dispersion. The doublet formed by the first three quadrupoles makes the beam convergent in both planes and Q1 produces a horizontal angular focus between Q2 and Q3. The vertically focussing component of the doublet is split so that a collimator H can be placed at the horizontal angular focus. Consequently, the definition of the horizontal angular acceptance is, to first order, independent of the target width. Momentum dispersion is provided by the bending magnets M1, M2 and M3. Q4 is used to produce a horizontal image of H at the counter hodoscope S_1. In the vertical plane the angular acceptance is defined by collimator V behind Q3. The doublet formed by Q5 and Q6 keeps the beam small in both planes as it passes through the remainder of the counter system.

A parallel beam of particles leaving the target at an angle $\delta\theta$ relative to θ_o is brought to a point focus at H. The distance of this point from the axis is proportional to $\delta\theta$, i.e.

$$x_1 = a_1\delta\theta \tag{3}$$

Since H is imaged onto S_1, the distance from the axis of a particle at S_1 would again be proportional to $\delta\theta$ but the bending magnets introduce a momentum dependence into the displacement. Using the momentum relation given in eq.(2), we can express the total horizontal displacement at S_1 as

$$x_2 = a_2\delta\theta + D(G\delta\theta + \delta p/p_o)$$

where D is the momentum dispersion of the spectrometer. If we define a spectrometer slope

$$S(D) = - a_2/D \tag{4}$$

then

$$x_2 = D(G - S)\delta\theta + D\delta p/p_o.$$

The line broadening (fig.2b) due to the finite angular acceptance of the spectrometer can be eliminated if the dispersion is chosen such that G=S (fig.2c). The resolution is then optimal and

$$x_2 = D\delta p/p_o \tag{5}$$

In other words, each point in the image plane corresponds to a definite value of the missing-mass.

The momentum band accepted by the spectrometer is defined by the horizontal width of the hodoscope S_1 which is composed of 10 elements each of 0.8 cm horizontal width mounted in a plane perpendicular to the spectrometer axis. Each element has an acceptance window in the (p-θ)-plane parallel to the curves of constant M^*. The i^{th} element accepts momenta between $p_i(1 - \varepsilon/2)$ and $p_i(1 + \varepsilon/2)$, where $\varepsilon = 0.8/D$ (eq.(5)) and

$$p_i = p_o \left(1 + (5.5 - i)\varepsilon\right)$$

The spectrometer setting p_o corresponds to the point at the centre of the hodoscope. The acceptance of the hodoscope for the scattering of 5.89 GeV electrons at $\theta_o = 11.13^o$ is shown in fig.1.

2.2 Slope and Dispersion

The slope G for an electron-proton scattering reaction is obtained by differentiating eq.(1) with respect to θ, i.e.

$$G = -\frac{(E/M)\sin\theta}{1 + (2E/M)\sin^2\frac{1}{2}\theta}$$

The spectrometer is designed to operate at scattering angles between 8^o and 35^o and at incident energies up to 6 GeV. In this region G varies from 0 to 1.73 radian^{-1} so that it is necessary to vary the dispersion (eq.(4)) to keep the spectrometer slope equal to G. This is accomplished by changing the bending angles of M2 and M3. In terms of the combined bending angle β, the dispersion (in cm) is

$$D = -(0.705 + 6.34\,\beta)\cdot 10^2 .$$

The negative sign is a consequence of our choice of the positive x-direction. The factor 0.705 is due to the deflection of 6.66^o produced by M1. The parameter a_2 is $-2.048\cdot 10^2$ cm/radian, therefore the spectrometer slope is

$$S = - \frac{2.048}{0.705 + 6.34\,\beta} ,$$

where β can be varied from 4° to 16°. The minimum value of β gives a maximum value for S of 1.79 radian^{-1}, which is slightly greater than is necessary. In principle, the minimum required slope is zero. Since this can only be obtained if the dispersion is infinite, the lower limit on S is determined by technical limitations on the maximum attainable dispersion. The maximum value of β gives $S = 0.83 \mathrm{radian}^{-1}$. This is sufficiently small for most practical purposes.

In a spectrometer designed to operate at small scattering angles, geometrical restrictions require that the scattered particles be deflected away from the incident beam direction. This means that with our sign convention the dispersion is negative. Therefore, to obtain the required negative slope, the parameter a_2 (eq.(4)) must also be negative. It is for this reason that an intermediate angular focus is required.

2.3 Angular Acceptance and Solid Angle

The intermediate focal plane is an ideal place to define the mean horizontal scattering angle and angular acceptance. Since $x_1 = a_1 \delta\theta$ (eq.(3)), the collimator H provides a definition of the horizontal acceptance that, to first order, is independent of the target size. The horizontal acceptance of 24 milliradians (corresponding to a collimator opening of 4.26 cm) was chosen such that the transmission of particles would be limited only by the collimator.

In the vertical plane the acceptance is defined by the collimator V. The opening is 16 cm and the angular acceptance is 18.22 milliradians. The beam size at the rear of the spectrometer is sensitive to both the effective vertical target size and, because of chromatic aberrations, to the size of the accepted momentum band. To ensure that all particles in the momentum band defined by S_1 are transmitted through the remainder of the detection system, it is necessary to limit the vertical size of the incident beam to about ±0.2 cm. The effect of the vertical target size on the angular acceptance is then negligible.

To first order the solid angle is given by the product of the mean vertical and horizontal angular acceptances, i.e.

$$\Delta\Omega = 0.4373 \text{ millisteradians}$$

This figure has to be corrected for edge effects due to the finite thicknesses of the collimators and for target size effects in the horizontal acceptance. These corrections amount to about 1% for a 10 cm diameter target, which is the largest size that has been used. Chromatic aberrations make the solid angle slightly dependent on $\delta p/p_o$. If $\Delta\Omega_o$ is the solid angle at the centre of the hodoscope ($\delta p/p_o = 0$), then

$$\Delta\Omega = \frac{\Delta\Omega_o}{1 + 1.544\ \delta p/p_o}$$

is the solid angle at a point in the hodoscope distant $D\delta p/p_o$ from the centre. The maximum size of the accepted momentum band is ±3.18% corresponding to the minimum dispersion. Consequently, the maximum variation of Ω across S_1 is about ±5%.

3. CONSTRUCTION AND EXPERIMENTAL ARRANGEMENT

3.1 The Magnet System

The physical composition of the spectrometer and the system of counters used for particle detection and identification are shown in fig.3. The magnet elements up to and including M2, the horizontal and vertical collimators and 65 tons of concrete shielding are mounted on the main platform. This platform, which is 25.5 m long, is supported on rollers which roll on three carefully aligned steel rails and allow the spectrometer to be rotated through the angular range $0^o - 35^o$. However, it is not possible to operate at scattering angles between 0.5^o and 8^o since the incident beam would strike the first quadrupole.

The platform is designed to carry the total magnet and shielding load of 190 tons with the magnet alignments maintained to ±0.2 mm. The magnetic elements are standard DESY quadrupoles and bending magnets with gradients, field strengths and magnetic lengths known to 0.1%. The horizontal and vertical collimators are rectangular slits defined by pieces of sintered tungsten 5 cm and 6cm thick respectively. A vacuum of 10^{-1} torr is maintained between the target and the hodoscope.

All components after M2 are mounted on a second platform which rotates on the main platform about a turning point at the exit of M2. The appropriate spectrometer slope in the (p-θ)-plane is chosen by changing the deflection angles in M2 and M3 and by adjusting the angle of the upper platform to obtain the correct total bending angle β.

3.2 Particle Detection and Identification

The momentum band accepted by the spectrometer is defined by the horizontal widths of S_1 and S_2. The spectral shape of the momentum distribution is registered by the 10 counter elements of S_1 and the integral of the distribution is recorded by S_2. They are mounted inside a thick-walled lead castle with S_2 20 cm behind S_1. Both counters are 8 cm square. Electrons are identified in the gas-filled threshold Čerenkov counter following S_2 and registered in counters S_3, S_4, S_5, and S_6.

The Čerenkov counter, which extends through quadrupoles Q5 and Q6, is 5.5 m long and has an internal diameter of 26 cm. Ethylene is normally used as a radiator. When the pressure is properly adjusted the counter has an efficiency of (99.7 ± 0.3)% for counting electrons but is insensitive to muons and heavier particles. Electron identification is done in the 5 different coincidence channels: $(S_1 S_3 S_5)$, $(S_2 S_4 S_6)$, $(S_1 \check{C}\, S_3 S_5)$, $(S_2 \check{C}\, S_4 S_6)$, $(S_1 S_2 S_3 S_4 S_5 S_6)$. Comparison of channels with and without the Čerenkov counter serves to monitor the rejection of background particles.

The counters S_3, S_4, S_5, and S_6 are mounted inside a second lead castle behind the Čerenkov counter. S_4 and S_6 are, respectively, about 20% larger than S_3 and S_5 so that comparison of even and odd channels serves as a continuous check on the spectrometer optics and the functioning of the counters and electronics.

4. PERFORMANCE

The spectrometer has been successfully used in an electron-proton scattering experiment[6)] in which the elastic scattering cross section was measured with a precision of about 5% at momentum transfers between 10 and 105 f^{-2}. A typical momentum spectrum taken during this experiment is shown in fig.4. The elastic peak and part of the radiative "tail" are shown for the scattering of 5.275 GeV electrons at $\theta_o = 12.5^o$. The determination of the resolution from such a spectrum is complicated by the fact that, in addition to the inherent line width, the particle distribution is due to radiative effects, momentum spread in the incident beam and to the finite momentum acceptance of the hodoscope elements. One can conclude, however, that the total line width is smaller than the counter acceptance of 0.42 %.

Because the counting rate at small angles is very high, an attempt was made to determine the line width by changing the spectrometer setting in steps significantly smaller than the counter acceptance. The variation of the counting rate with the magnet setting is shown in fig.5 for hodoscope elements 4, 5 and 6. The width of these curves is characteristic of the counter width while the rate of rise is given by the line width. The data indicate a line width of (0.23 ± 0.04)%. Since the momentum spread in the incident beam was about 0.2%, we estimate that the inherent spectrometer line width under these conditions is at least as good as the calculated value of 0.16%.

At large scattering angles the calculated line widths are larger than the momentum spread in the incident beam, so that one should be able to obtain more accurate values for the resolution than are possible at small angles. A momentum spectrum taken for the scattering of 5.885 GeV electrons at 25° showed that the total line width was again better than the counter acceptance of 0.64%. For these conditions it was not possible to determine the line width by varying the spectrometer setting since the cross section is very small. Consequently, we can conclude only that the inherent line width is better than 0.64%.

ACKNOWLEDGEMENTS

We are very much indepted to Mr. Daßkowski under whose direction the platform was built and installed and who constructed most of the other mechanical parts of the spectrometer. The functioning of the spectrometer depends largely on the excellent survey work done by Mr. Loeffler and his co-workers, to whom we extend our thanks.

It is a great pleasure to acknowledge the co-operation of the groups of Dr. Degèle, Mr. Bothe and Mr. Kumpfert in planning, setting-up, and using the spectrometer.

We want to thank Mr. Maegli, Masbender, Lüthke, Rogner, and Schwartz for technical help during all phases of the project.

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FIGURE CAPTIONS

Fig.1 The variation of scattered momentum with production angle for an incident energy of 5.89 GeV. The curves shown correspond to elastic scattering ($M^* = M = 0.9382$ GeV) and single pion production at threshold ($M^* = 1.074$ GeV). The insert shows the acceptance window of the 10-counter hodoscope at $\theta_o = 11.13^o$.

Fig.2 Particle trajectories in the horizontal and vertical planes.

(a) Horizontal plane trajectories showing the positions of the focal and image planes.

(b) Horizontal trajectories when $G \neq S$.

(c) Horizontal trajectories when the matching condition is satisfied.

(d) Vertical trajectories showing the effects of target size and chromatic aberration on the beam size at the rear of the spectrometer.

Fig.3 The spectrometer and the particle detection and identification system. 5 cm and 10 cm long liquid hydrogen targets (T) have been used.

Fig.4 The elastic peak and radiative "tail" recorded by the 10-counter hodoscope for the scattering of 5.275 GeV electrons from protons at $\theta_o = 12.5^o$. The momentum acceptance of each hodoscope element was 0.42 %.

Fig.5 The elastic peak recorded by hodoscope elements 4, 5 and 6 when the spectrometer setting was varied in steps of 0.1%. The slower decrease in the counting rate on the low momentum side of the curves is due to the radiative "tail".

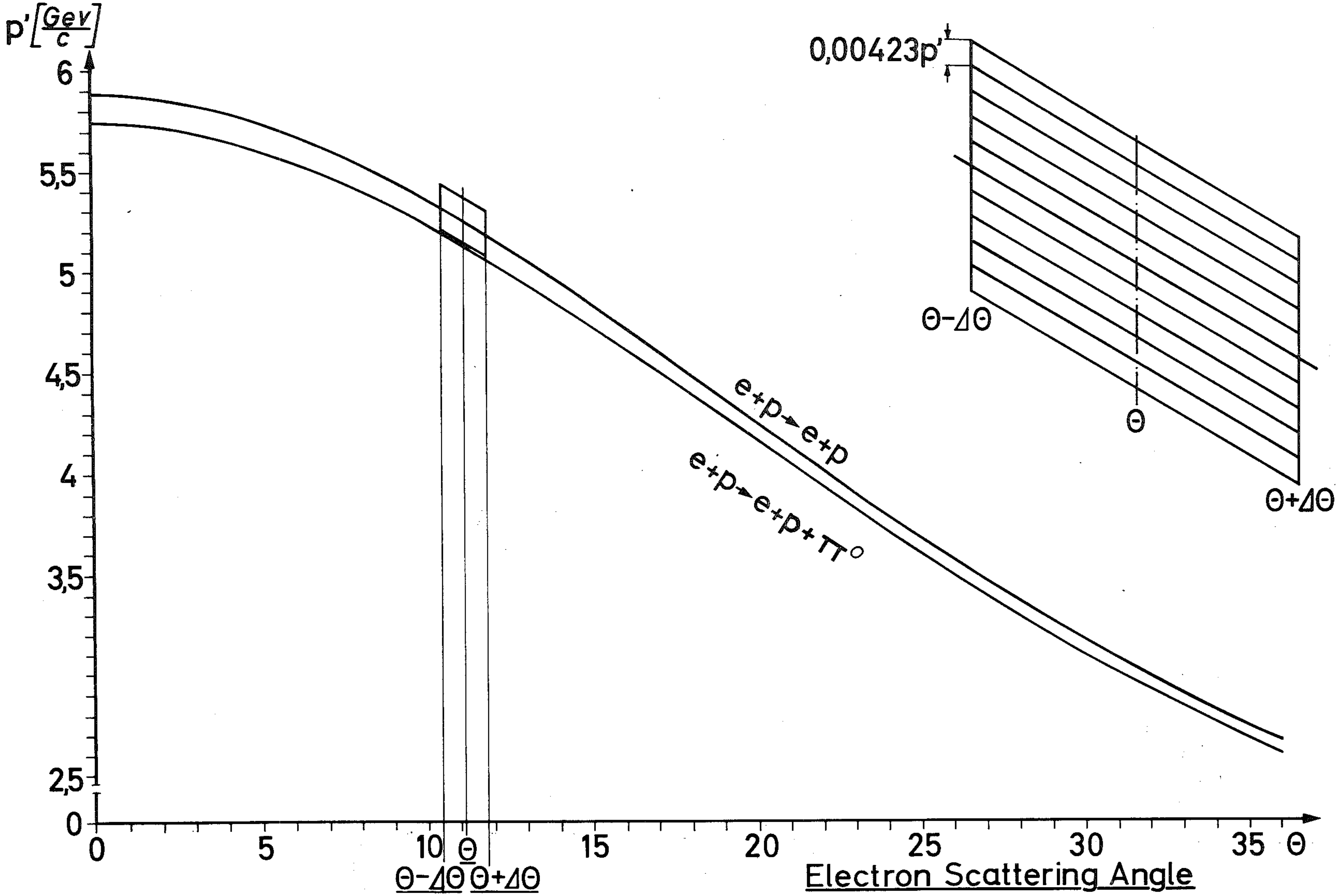
p' [GeV/c]
6
5,5
5
4,5
4
3,5
2,5
0
0
5
10
Θ
15
20
25
30
35
Θ
Θ-ΔΘ
Θ+ΔΘ
Electron Scattering Angle
e+p→e+p
e+p→e+p+π°
0,00423p'
Θ-ΔΘ
Θ
Θ+ΔΘ

FIG. 1

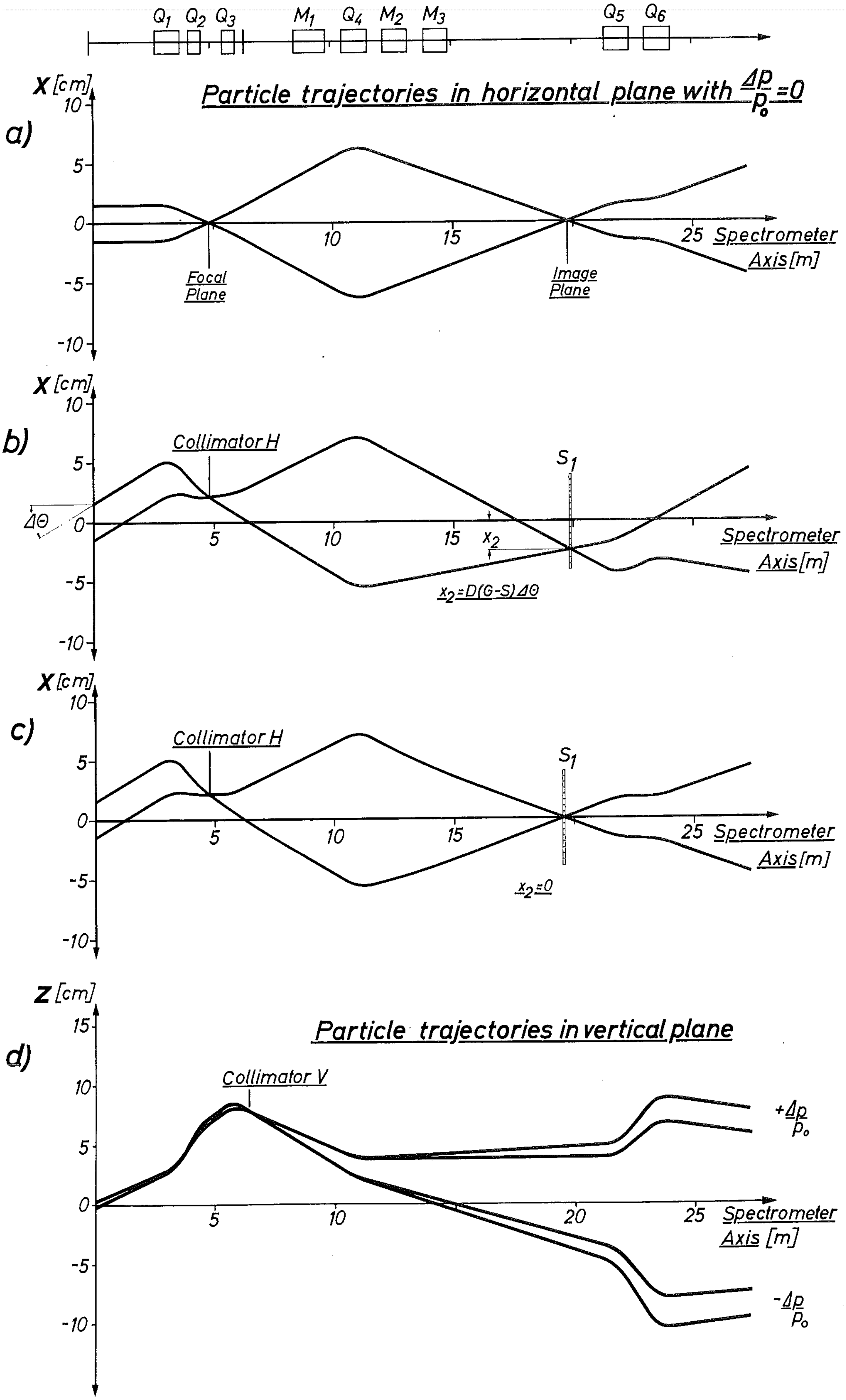
Q1
Q2
Q3
M1
Q4
M2
M3
Q5
Q6
Particle trajectories in horizontal plane with Δp/p0 =0
a)
X [cm]
10
5
0
-5
-10
10
15
25
Spectrometer Axis [m]
Focal Plane
Image Plane
b)
X [cm]
Collimator H
S1
ΔΘ
x2
x2=D(G-S)ΔΘ
Spectrometer Axis [m]
c)
X [cm]
Collimator H
S1
x2=0
Spectrometer Axis [m]
Particle trajectories in vertical plane
d)
Z [cm]
15
Collimator V
+Δp/p0
-Δp/p0
20
Spectrometer Axis [m]

FIG. 2

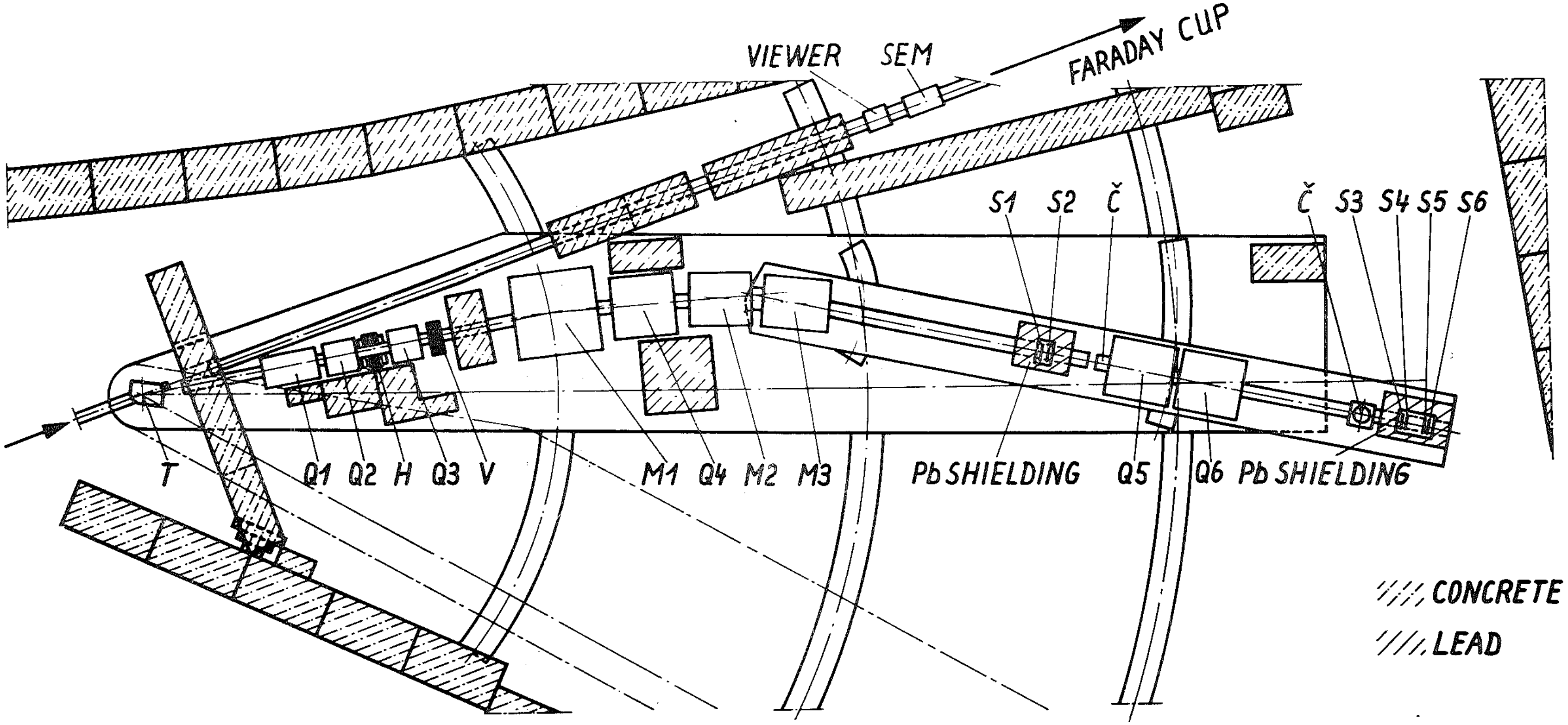
VIEWER
SEM
FARADAY CUP
S1
S2
Č
Č
S3
S4
S5
S6
T
Q1
Q2
H
Q3
V
M1
Q4
M2
M3
Pb SHIELDING
Q5
Q6
Pb SHIELDING
CONCRETE
LEAD

FIG. 3

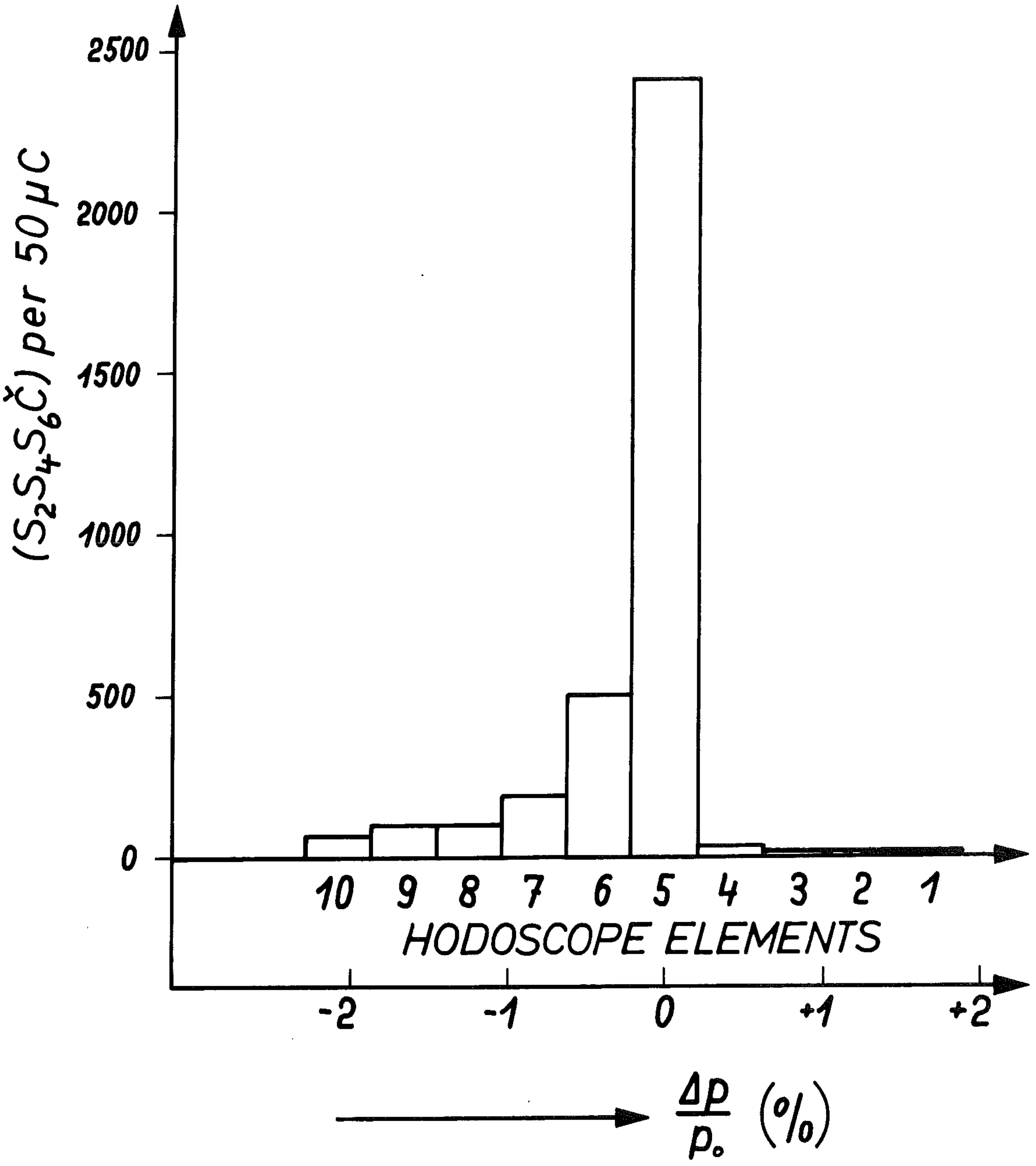
2500
2000
1500
1000
500
0
$(S_2 S_4 S_6 \check{C})$ per 50 μC
10
9
8
7
6
5
4
3
2
1
HODOSCOPE ELEMENTS
-2
-1
0
+1
+2
$\frac{\Delta p}{p_o}$ (%)

FIG. 4

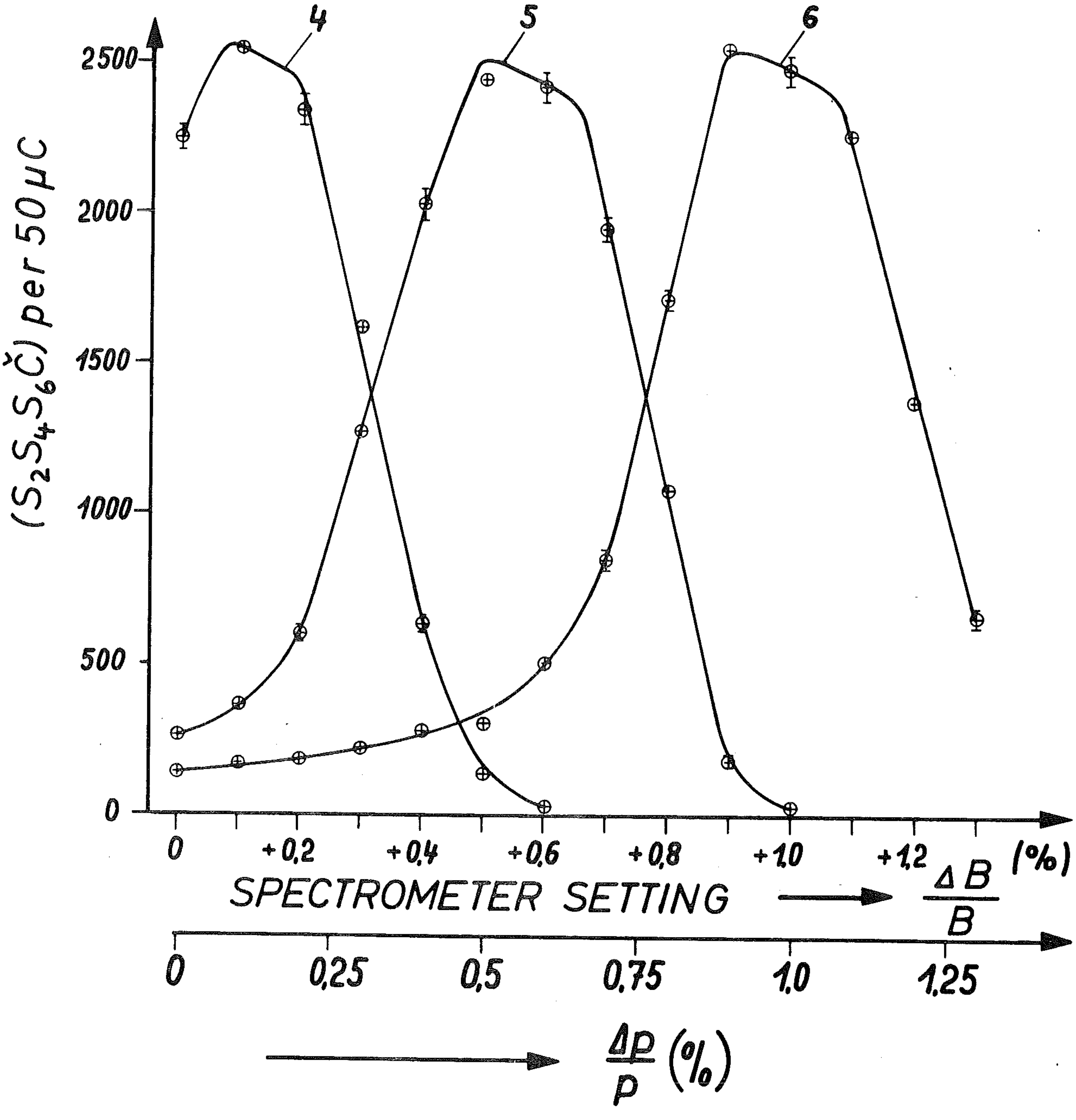
4
5
6
($S_2S_4S_6\check{C}$) per 50 μC
2500
2000
1500
1000
500
0
0
+0,2
+0,4
+0,6
+0,8
+1,0
+1,2
(%)
SPECTROMETER SETTING
$\frac{\Delta B}{B}$
0
0,25
0,5
0,75
1,0
1,25
$\frac{\Delta p}{p}$ (%)

FIG. 5