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Authors
Murray, Joseph J.
Button-Shafer, Janice
Shively, Frank T.
et al.

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Ernest O. Lawrence Radiation Laboratory

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(Presented by George R. Kalbfleisch)

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In mid-1963 a new separated K^- beam was brought into operation at the Lawrence Radiation Laboratory, and for the past year a 72-inch hydrogen bubble-chamber run, designated "K-63," has been carried out at beam momenta of 2.5, 2.6, 2.7, and 2.8 GeV/c with an exposure of about 500 000 pictures. (Concurrently an exposure of about 750 000 pictures was made with π^- beams at various momenta from 2 to 4 GeV/c, using the same beam apparatus.)

In overall configuration the beam is a conventional two-stage system, but the optical design is unique in that a new method was used to eliminate chromatic aberration which does not require the use of magnets with sextupole field components. The mass slits, usually perpendicular to the beam direction, are tilted severely so that a line along the apex of the slits makes an angle in the horizontal plane of only a few degrees with respect to the beam direction. With this arrangement it was possible to design the beam optics so that stigmatic foci are formed nearly independent of momentum at the mass slits of both the first and second stages. The result is virtual elimination of chromatic aberration over a momentum interval of 4%. Primarily the purpose of this paper will be to elucidate the foregoing technique of achromatization. For this purpose it is unnecessary to delve into all the detailed design of the beam and sufficient to consider only the optics in the vicinity of the mass-resolving slits.

A coordinate system will be used in which the Z axis is along the beam direction and the X and Y axes are vertical and horizontal, respectively. Angles in the XZ (vertical), YZ (horizontal), and XY (transverse) plane will be denoted by ϕ, θ, and ψ, respectively. In this discussion finite source size and the corresponding finite separation of the mass slit jaws will be ignored and the surfaces of the slit jaws will be represented simply as two intersecting planes, viz.:

$$\mp X \cot \psi_s + Y - Z \tan \theta_s = 0$$

or (1)

$$\pm X \cot \phi_s + Y \cot \theta_s - Z = 0,$$

$$\tan \psi_s = - \tan \phi_s / \tan \theta_s,$$

where ϕ_s and θ_s are angles between the Z axis and the lines of intersection of the planes of the slit jaw with the XZ and YZ planes, and ψ_s is the corresponding angle with respect to the Y axis in the XY or transverse plane. The + or - sign distinguishes the upper and lower surfaces of the slit jaws.

Suppose the origin of the coordinate system is at the center of the mass slit and let the optical matrices connecting the target and the point Z in the vertical and horizontal planes be given by

$$\begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha & \beta \\ \delta & \gamma \end{bmatrix} = \begin{bmatrix} \alpha + Z\delta & \beta + Z\gamma \\ \delta & \gamma \end{bmatrix} \text{ — vertical ,}$$

(2)

$$\begin{bmatrix} 1 & Z & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a & b & g \\ c & d & h \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} a + Zc & b + Zd & g + Zh \\ c & d & h \\ 0 & 0 & 1 \end{bmatrix} \text{ — horizontal,}$$

where the corresponding ray vectors are

$$\begin{bmatrix} X_i \\ \phi_i \end{bmatrix} \text{ vertical, and } \begin{bmatrix} Y_i \\ \theta_i \\ \Delta \end{bmatrix} \text{ horizontal,}$$

and Δ is the fractional deviation of momentum from the central momentum. Chromatic aberration can be considered in terms of the momentum dependence of the matrix elements. These are complicated dependences related in general to details of the entire beam. In the subsequent analysis the matrix elements will be expanded in power series in Δ, e.g., $\beta = \beta_0 + \beta_1 \Delta + \cdots$, but the only terms retained will be those leading to final expressions linear in both Δ and Z. An expression for the solid angle accepted by the mass slit will now be obtained from which the conditions for achromatization or momentum independence of the acceptance will be deduced.

The displacements of rays in the vicinity of the mass slit which originate from a point source ($X_i = Y_i = 0$) with angles ϕ_i and θ_i at the source are, from Eq. (2),

$$\begin{aligned} X &= (\beta + Z\gamma)\,\phi_i, \\ Y &= (b + Zd)\theta_i + (g + Zh)\Delta. \end{aligned} \tag{3}$$

It will be assumed that for $Z = \Delta = 0$ there is a stigmatic focus so that appropriate lowest-order expansions of the relevant matrix elements will be

$$\beta = \beta_1 \Delta, \; b = b_1 \Delta$$

($\beta_0 = b_0 = 0$ gives a stigmatic focus at $Z = \Delta = 0$),

$$\gamma = \gamma_0 = 1/M_V, \; d = d_0 = 1/M_H,$$

$$g = g_0,$$

where M_V and M_H are the vertical and horizontal magnifications, respectively. The ray displacements in the vicinity of the mass slit are bounded by the plane surfaces of the slit jaws. The combination of (1) and (3) and use of the foregoing expansions of the matrix elements yields the following relationship between ϕ_i and θ_i, which defines the boundaries of the region in

ϕ_i, θ_i space accepted by the mass slit:

$$\begin{aligned} &\pm (\beta_1 \Delta + Z/M_V) \cot \phi_s \, \phi_i \\ &+ (b_1 \Delta + Z/M_H) \cot \theta_s \, \theta_i \\ &+ g_0 \cot \theta_s \Delta - Z \qquad = 0. \end{aligned} \tag{4}$$

Achromatization results in general when

$$\beta_1 M_V = b_1 M_H = -g_0 \cot \theta_s, \tag{5}$$

that is, when the vertical and horizontal foci are stigmatic for all Δ and when the apex of the slit jaws or intersection of the plane surfaces of the slit jaws lies along the locus of the stigmatic focus. In this case (4) reduces to

$$(Z - g_0 \Delta \cot \theta_s) (\pm \phi_i \cot \phi_s / M_V + \theta_i \cot \theta_s / M_H - 1) = 0,$$

or, in terms of final angles $\phi = \phi_i / M_V$ and $\theta = \theta_i / M_H$,

$$\pm \phi \cot \phi_s + \theta \cot \theta_s - 1 = 0. \tag{6}$$

An exceptional case occurs when $\beta_1 = \cot \theta_s = 0$. Then b_1— and in fact b_0— can have any values. This is the situation achieved when magnets with sextupole field components are included in the beam optical system in such a way that β_1 can be forced to equal zero. Equation (6) then becomes $\pm \phi \cot \phi_s - 1 = 0$ and the region of achromatic acceptance is simply a strip parallel to the θ axis bounded by $\phi = \pm \tan \phi_s$. Achromatization by the sextupole technique is not always convenient and involves incidental optical aberrations which can limit its usefulness.

The achromatic acceptance region defined by Eq. (6) when $\cot \theta_s \neq 0$ is illustrated in Fig. 1. Typically the acceptance of a separated beam exclusive of the mass slit will be almost rectangular. Such a region is shown as a dashed rectangle in Fig. 1 fitted into the acceptance region presented by the mass slit and bounded by ϕ_m and θ_m, the half angles of acceptance determined by apertures other than the mass slit. By inspection of Fig. 1 the following relationships are obtained which, together with the condition for achromatization, Eq. (5), define the geometry of the slit jaws:

$$\begin{aligned} \tan\psi_s &= \phi_m/(\tan\theta_s - \theta_m), \\ \tan\phi_s &= -\phi_m[\tan\theta_s/(\tan\theta_s - \theta_m)]. \end{aligned} \tag{7}$$

From the last one of the above equations one can see the principal drawback in the use of the tilted-slit method of achromatization; namely, the effective vertical divergence of the slit is increased by the factor $\tan\theta_s/(\tan\theta_s - \theta_m)$ compared to the divergence required for a slit with its apex perpendicular to the beam direction. Hence the effective thickness of the slit jaw is correspondingly reduced. For small separations inevitably encountered when a separated beam is pushed to its limit, the reduction in slit-jaw thickness can be the limiting factor. In general θ_s must be much larger than θ_m.

Values of parameters relevant to the foregoing discussion which were determined in the design of the K-63 beam are listed in Table I.

The slits are severely tilted (small θ_s) and elongated in the beam direction as indicated by the large values of $g_0 \cot\theta_s$. Measured in a direction perpendicular to the apex, the slit jaws were 1 in. thick — ample to realize maximum effective rejection for particles incident in the beam direction. When as in the present instance θ_s is small, ψ_s is approximately equal to the divergence angle of the slit jaw in a plane perpendicular to the apex of the slit, which is the angle most convenient for specifying the construction of the slit jaw.

To illustrate the overall beam configuration, a schematic of the layout of beam apparatus is shown in Fig. 2. The only feature of the configuration dictated solely by the requirements of tilted-slit achromatization is the inclusion of a singlet quadrupole element just ahead of each mass slit.

For reasons probably obvious, the degree of freedom provided by this magnet is essential in order to ensure stigmatism of the vertical and horizontal images, that is, to satisfy the achromatic condition $\beta_1 M_V = b_1 M_H$.

The overall optical features of the beam are indicated by the ray-trace diagrams shown in Figs. 3 and 4, which were obtained by analog computation.[1] In both stages the beam in the separators is approximately parallel in the vertical plane with focal lengths of about 350 in. and target height and slit widths all equal to 1/16 inch. The separators are equipped with glass cathodes and are operated at about 500 kV with 2-in. gaps.

FOOTNOTE AND REFERENCE

[*] Work sponsored by the U. S. Atomic Energy Commission.

1. For details of optical design and magnet studies, reference may be made to Alvarez Physics Memos No. 519, July 1964, and No. 518, July 1964 (Lawrence Radiation Laboratory, unpublished).

Table I. Values of various parameters pertinent to the "tilted mass slit" method of achromatization used in the K-63 separated K^- beam.

Parameter	First stage	Second stage
ϕ_m	2.7×10^{-3} rad	3×10^{-3} rad
θ_m	9×10^{-3} rad	8×10^{-3} rad
M_V	-0.9	-0.9
M_H	-1.1	-1.1
g_0	0.5 in./%	0.5 in./%
$g_0 \cot \theta_s$	10 in./%	20 in./%
θ_s	50×10^{-3} rad	25×10^{-3} rad
ϕ_s	3.3×10^{-3} rad	4.4×10^{-3} rad
ψ_s	65×10^{-3} rad	176×10^{-3} rad

FIGURE CAPTIONS

Fig. 1. Acceptance diagram in the space of the vertical and horizontal ray angles at the mass slit for a separated beam achromatized by tilting the apex of the mass slit.

Fig. 2. Schematic layout of K-63 beam apparatus.

Fig. 3. Ray trace diagrams for first stage of K-63 beam.

Fig. 4. Ray trace diagrams for second stage of K-63 beam.

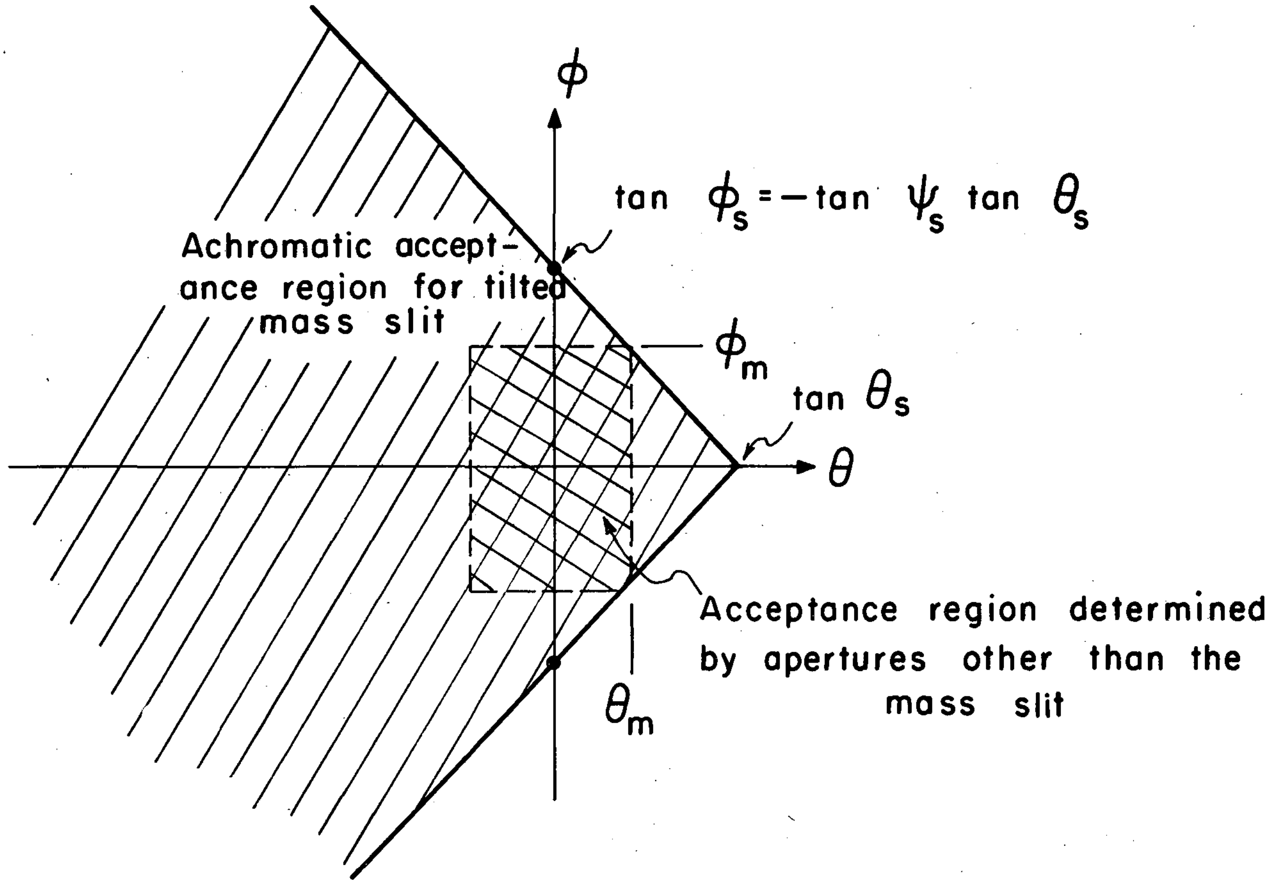

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Fig. 1

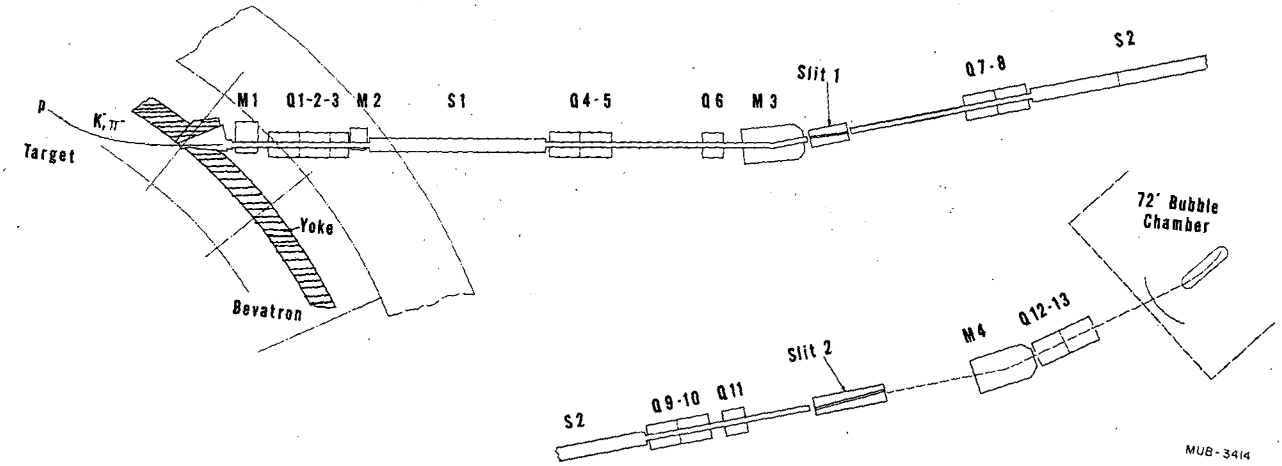

p
K^-, π^-
Target
Yoke
Bevatron
M1
Q1-2-3
M 2
S 1
Q 4 - 5
Q 6
M 3
Slit 1
Q 7 - 8
S 2
72″ Bubble Chamber
Q 12-13
M4
Slit 2
Q 11
Q 9 - 10
S 2
MUB-3414

Fig. 2

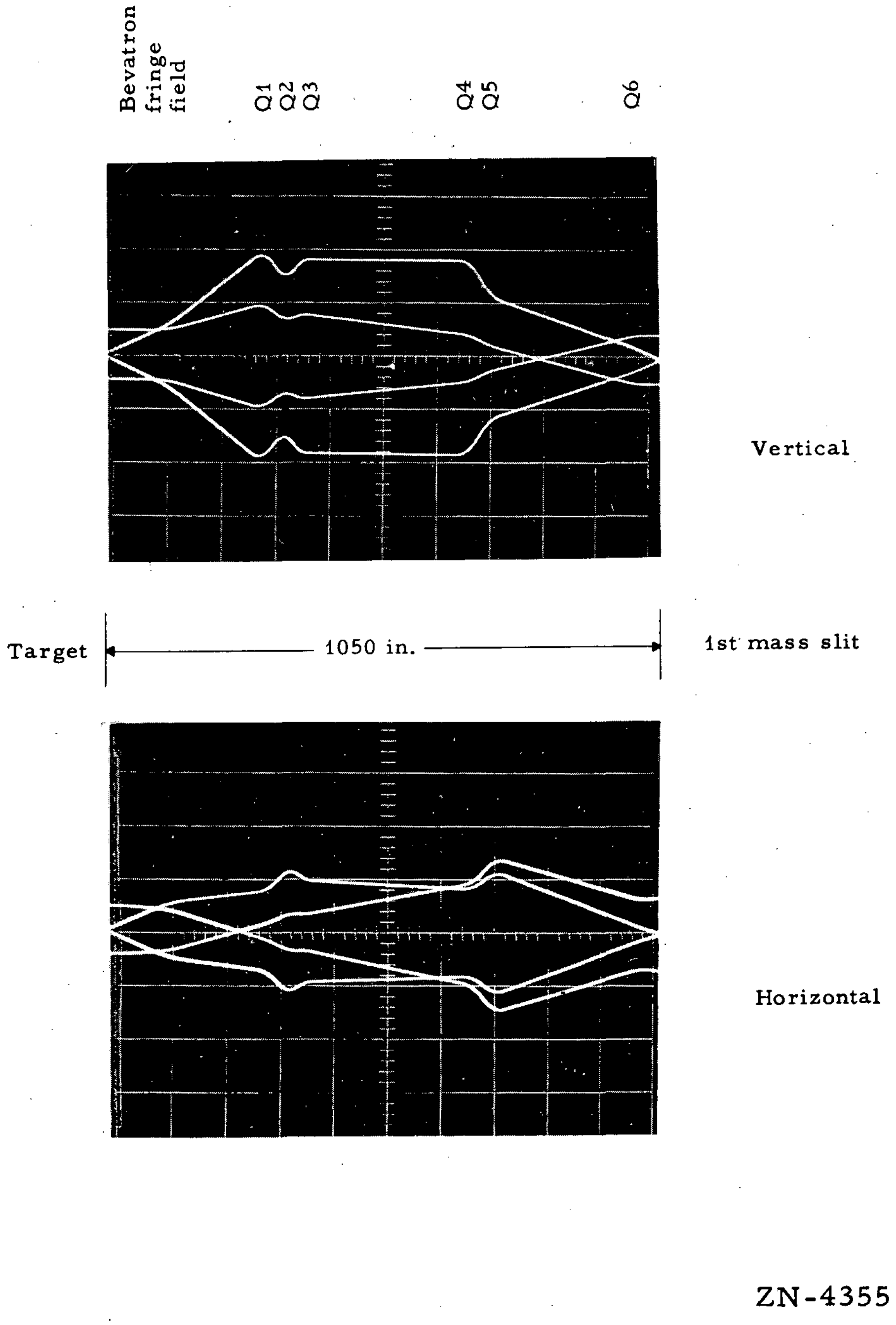
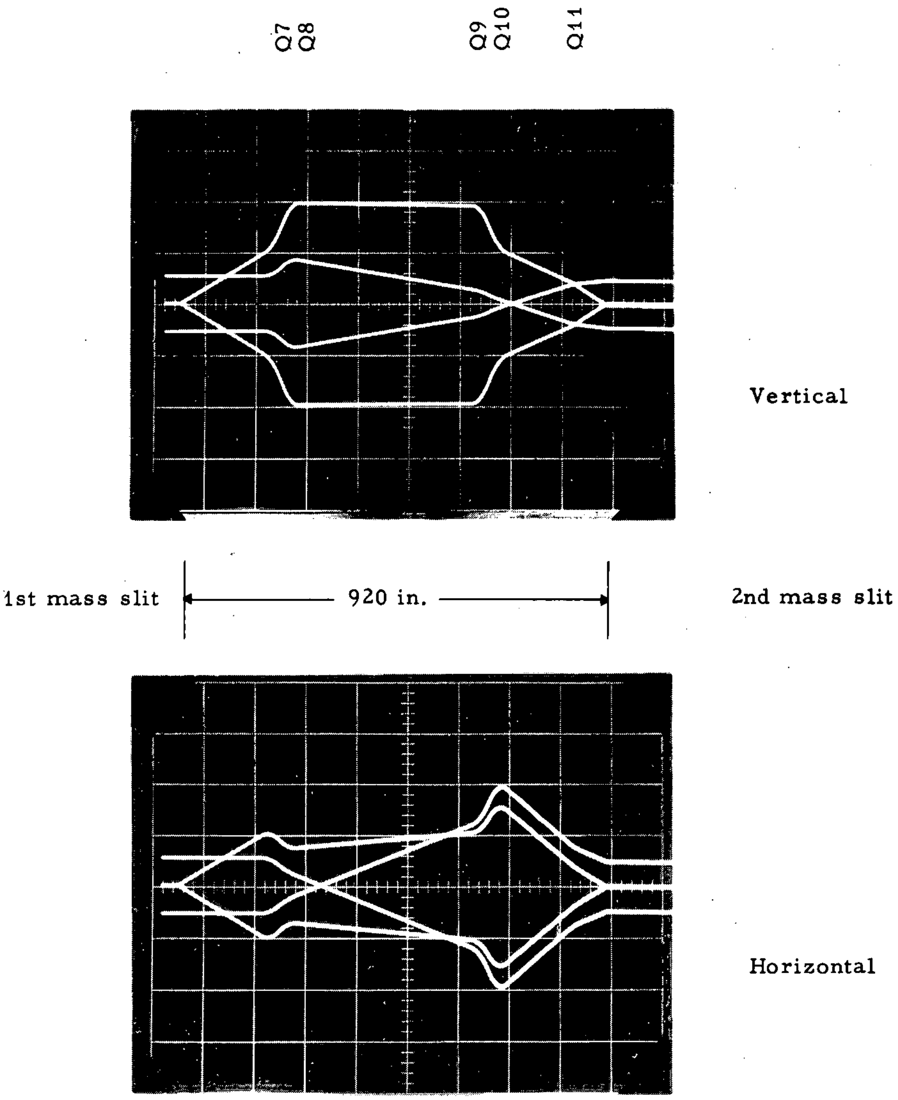

Bevatron fringe field
Q1
Q2
Q3
Q4
Q5
Q6
Vertical
Target
1050 in.
1st mass slit
Horizontal
ZN-4355

Fig. 3


Q7
Q8
Q9
Q10
Q11
Vertical
1st mass slit
920 in.
2nd mass slit
Horizontal

ZN-4356

Fig. 4