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I. INTRODUCTION

In the early days, low-energy K, π beams were separated successfully through the so-called degrader method that worked by virtue of the velocity dependence of the ionization loss of charged particles in matter. The method is subject to difficulties connected with multiple Coulomb scattering and nuclear degradation in the energy-loss target, and extrapolates poorly to high energy because of rapid loss of sensitivity to particle velocity. Only the method is amiss, however, not necessarily the principle. It seems clear, for example, that the difficulties of the degrader method would be avoided if rf linear acceleration were used to produce the longitudinal momentum modulation. But the question arises whether such a method would have any merit relative to electrostatic methods, and rf methods involving transverse momentum modulation. It is the purpose here to point out why the author thinks the answer is affirmative, and to consider briefly a more or less specific linearly separated beam design which is emerging at the Lawrence Radiation Laboratory, Berkeley, in connection with plans for a 4-GeV/c K^- beam.

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II. GENERAL FEATURES OF A LINEARLY SEPARATED BEAM

Schematically, the simplest linearly separated beam would consist of two beam-transport sections with momentum resolution in each, and with an rf linear accelerator between them. The linear accelerator might be continuous or broken into two sections depending on the amount of acceleration needed. The length overall and the phase velocity of the accelerating field, as in any other rf separating system, would be chosen to give a net aero-acceleration at the velocity of one mass component of the beam, and a maximum acceleration at the velocity of another (or a reasonable approximation to this extreme condition). Nominally complete separation of the mass components would require that the unwanted particles be unmodulated and removed on a stopper at the point of final momentum resolution, while the wanted particles having a spatial deflection periodic at the rf frequency at that point would be collected around or at one side of the stopper with an inefficiency.

Since a momentum-resolving deflection effects the actual separation of the masses, while in the accelerator itself no transverse deflection takes place, a compatible situation arises in which the beam-transport optical system is required alternately to compress and expand the beam spatially for passage through the accelerator and bending magnets, respectively. The acceptability of a spatially compressed (and angularly expanded) beam within the rf device is a point in favor of the linear method as compared with methods involving transverse deflection where the requirement is exactly the opposite, and must usually be compromised because of the limiting spatial aperture of the deflecting device.

III. PRELIMINARY REDUCTION OF THE PROBLEM TO A SPECIAL CASE

In order to eliminate needless generality, the subsequent discussion will be partly specialized to the case of a 4-GeV/c K, π beam. For that case, one can make the following tentative evaluation of the significant accelerator parameters. Let it be assumed that the rf accelerator must be operated in the S-band ($\approx$ 3000 kMc), if for no other reason than to minimize decay losses for K mesons. Let it be further assumed that a circular disc-loaded accelerating wave guide is used and that, in accordance with Stanford University experience, the accelerator can be operated at a power level of about 0.5 Mw/ft with a corresponding acceleration of about 2 MeV/ft.

For K,π velocities at 4 GeV/c, the flight path corresponding to a phase slip of one complete cycle at 3 kMc is 46 feet. With no good reason to economize on accelerator length without appreciable reduction in overall length, which will be considerably more than 46 feet, the optimum accelerator will be assumed to approximately fill the entire 46-ft length. One would expect then, with the phase velocity set equal to the K velocity, to get about 2% peak K momentum modulation and zero net π momentum modulation. The actual accelerator might consist of four approx 10-ft-long independent sections, each powered with a single klystron.

IV. ACCELERATOR ACCEPTANCE

Because transverse deflection is absent in the accelerator as mentioned above, the phase space transmitted through it may have any configuration within the limits of its spatial aperture without impairing the ultimate separability of the beam. Advantage may be taken of this circumstance to enhance transmission by enclosing the accelerator in a strong focusing channel comprising a series of quadrupole magnets, in the present example perhaps 8 or more close-spaced 4-in.-bore quadrupole magnets. One may discuss the optics of such a channel in terms of approximate orbits that are sinusoidal in the symmetry planes with a wavelength given by

$$\lambda = \frac{2p}{(dB/d\rho)L} ,$$

where p is momentum, L is the effective length of a quadrupole element, and $dB/d\rho$ is the transverse magnetic field gradient in a symmetry plane. In order to image one end of the separator on the other, one needs $n(\lambda/2) = 46$ ft, corresponding to an optical matrix coupling the ends of the separator that is equal to 1 or -1 for n even or odd respectively. For $dB/d\rho = 5 \times 10^3$ kG/in., and with p = 4 GeV/c, this condition can be fulfilled for n = 2 if L = 24 in. We will assume that n = 2 can be realized practically. If d is the maximum acceptable beam diameter anywhere in the accelerator (equal to or less than the iris diameter), then the nominal phase area that can be transmitted in each symmetry plane is d^2/λ. For d = 1 in. this amounts to 11.4×10^{-3} in.-radians, which corresponds to a 2.6-msr solid angle accepted from a 1/4-in.-diam target. The effective acceptance in each plane would be reduced by the usual circular factor $\pi/4$, and by an additional factor perhaps as small as 2/3 in the practical case, with pseudo-discrete optical elements, where the extreme excursions of the beam exceed those of the idealized orbits assumed in the foregoing approximate analysis.

Without the aid of the strong-focusing channel, the phase area in one plane accepted by an accelerator of the same length ℓ and aperture d would be, at most,

$$\frac{d^2}{\ell} = \frac{1}{2\pi} \frac{d^2}{\lambda} ,$$

which suggests the importance of the strong-focusing channel, its effect amounting to more than an order of magnitude in beam intensity.

V. MOMENTUM ACCEPTANCE

With a 2% peak modulation, a momentum bite of roughly 1% should be acceptable, allowing some margin for spurious effects. Although the first momentum resolution in an optimized situation will yield a triangular momentum distribution function, the width of the distribution at the base may be allowed to equal 2% and still be equivalent in terms of image size to a 1% wide rectangular distribution if subsequent momentum-resolving deflections are alternated in such a way that dispersion does not build up. A typical bending magnet can provide up to 1.2×10^6 gauss-inches of deflection, which at 4 GeV/c and 1% momentum bite, gives an angular resolution of $\theta_p = 2.3 \times 10^{-3}$ radians. With an aperture of about 5×5 inches, and essentially the same optical conditions in both planes, one such magnet for each momentum resolution would be sufficient in the sense of compatibility with the accelerator acceptance.

VI. BACKGROUND REJECTION

Another point in favor of the linear method over methods involving transverse deflection in single-stage systems is that with a single accelerator the beam channel may be made opaque for both pions and muons from beam pion decays. In order to achieve this condition, momentum must be resolved twice ahead of the accelerator and twice after it. The momentum distributions of the rational flux and the background are illustrated schematically in Fig. 1 for each significant point along the beam which is diagrammed in Fig. 2.

After the first resolution, a substantial background with a broad momentum distribution will exist because of target halo (or its equivalent). The second resolution eliminates this background, leaving a residue of muons from beam pion decays with momenta on the low side only of the momentum distribution of the rational flux. After passage through the accelerator, the momentum distribution of the K component of the beam is periodically displaced above and below that of the pion component, the latter remaining fixed. At the third resolution a stopper is used, which eliminates the pions and all background components on the low side of the beam momentum distribution. At the same time, K's with a momentum distribution lying entirely above that of the unmodulated beam are accepted at one side of the stopper with an efficiency of about one-third, this factor representing an unfortunate disadvantage of the method in this application. Together with the K's there will be a residue of muons from pion decays that occurred after the third momentum -resolving deflection. This remaining background of muons, all with momenta lying below the K momenta, is eliminated by the fourth and final momentum resolution.

In some cases it is possible that the muon background remaining after the third momentum resolution is tolerable, and in that event the fourth momentum resolution could be omitted, and at the same time the K's could be collected on both sides of the stopper with better efficiency. There is no apparent reason why, with all four momentum resolutions, the ultimate background should not approach ambient level.

VII. PRE- AND POST-ACCELERATOR BEAM TRANSPORT

Usually the preaccelerator beam-transport system would be called upon to present as large a solid angle as possible at the target. Once determined, this solid angle in turn fixes the target size and magnification necessary to match the accelerator acceptance. Alternatively, there might be a minimum practical target size that would limit the solid angle to less than the maximum possible value.

In each momentum-resolving module of the beam-transport system the initial and final foci should be coupled with a unit optical matrix times the module magnification. In the continuous approximation this condition is automatically fulfilled. With discrete optical elements the equivalent of field lenses at the foci would be required, in addition to focusing lenses near the bending magnets. The overall magnification should probably be distributed more or less equally between the two momentum-resolving modules.

For the configuration that would result if an exposed target were used, the postaccelerator beam-transport system could very well be a mirror image of the preaccelerator system. In order to avoid irrelevancies, such a symmetrical system will be assumed and the semicontinuous approximation is used in the following estimate of overall beam dimensions.

For typical 8-inch-bore, 32-inch-long quadrupole magnets with $dB/d\rho = 3.1$ kG/in., the minimum optical wavelength λ_m at 4 GeV/c is 105 inches. With an effective aperture of a little more than 5×5 in., this corresponds to a solid angle at the target of about 2.5 msr which, in order to match the accelerator acceptance, must be associated with a 1/4-in. diam. target; these are curiously enough the same values that appeared in earlier illustrations. For an overall magnification of four, two in each module (needed to magnify the 1/4-in.-diam target to the 1-in. accelerator aperture), the following estimate may be made of lengths of the various segments of the preaccelerator beam-transport system (see Fig. 2):

Target to first bending magnet ($\pi/2\ \lambda_m$)	165 in.
First bending magnet (plus interference)	120
First bending magnet to first focus ($2\lambda_m$)	210
First focus to second bending magnet ($2\lambda_m$)	210
Second bending magnet	120
Second bending magnet to final focus ($4\lambda_m$)	420
Overall length of pre-accelerator system	1245

In the symmetrical case, this corresponds to an overall beam length of about 255 ft. Even though K decay losses (which here amount to a factor of 13) may be reduced by shortening the beam at the expense of acceptance, K intensity in the present example is maximized by maximizing acceptance.

VIII. K^- INTENSITY

An estimate of K^- flux equal to 0.11×10^{-9} $K^-/\%\,\Delta p$/msr/proton is available from measurements made in a 4-GeV/c Bevatron beam at near 0 deg laboratory angle by Cook et al.[1] Using their value for K^- flux at the target, the foregoing parameters lead to a predicted K^- flux, delivered, of 1 to 2 K's per 10^{12} protons on target. With a π^-/K^- ratio at the target[1] equal to 1.5×10^3, and with a separation ratio greater than about 5×10^4, which should be attainable, K's would predominate in the separated beam.

K^- flux increases rapidly with primary proton energy, typical results[2] with 25-GeV protons giving a value of about 0.34×10^{-6} $K^-/\%\,\Delta p$/msr/proton at 4 GeV/c K^- momentum (and about 10^{-2} times this amount at 10 GeV/c), or about 3×10^3 times the K^- flux at the Bevatron at 4 GeV/c.

IX. EXTRAPOLATION TO HIGHER MOMENTUM

With sufficient freedom in design, the following scaling relationships could hold:

Beam transport length	$\propto p$
Active accelerator length	$\propto p$
Distance between centers of the two halves of the accelerator, equivalent to a half-cycle phase slip for K,π (23 ft at 4 GeV/c)	$\propto p^2$
Nominal acceptance	$\propto 1/p^2$
Momentum bite	constant.

By extrapolation from the present example at 4 GeV/c, using these relationships, the following values are obtained for various parameters at 10 GeV/c:

Overall beam length	720 ft
Active accelerator length (in two major sections with centers 144 ft apart)	115 ft
Nominal acceptance	21×10^{-6} (in. -radians)

In spite of such an impressive length, K decay loss amounts only to a factor of 18. With primary K fluxes available at 25 GeV proton energy,[2] the acceptance of the linearly separated beam should make possible delivered K^- fluxes at 10 GeV/c of perhaps 5 per 10^{11} beam protons.

REFERENCES

1. V. Cook, et al., Phys. Rev. 123, 320 (1961).

2. W. W. Neale, A Proposal for a General Purpose Separated Particle Beam for Use with the British National Hydrogen Bubble Chamber in the East Experimental Area of the CERN Proton Synchrotron, CERN Report CERN/TC/NBC 62/1, February 13, 1962 (unpublished).

FIGURE CAPTIONS

Fig. 1. Schematic representation of the momentum distributions of the rational flux and backgrounds at each significant point along the beam.

Fig. 2. Schematic layout of beam apparatus and idealized ray diagram.

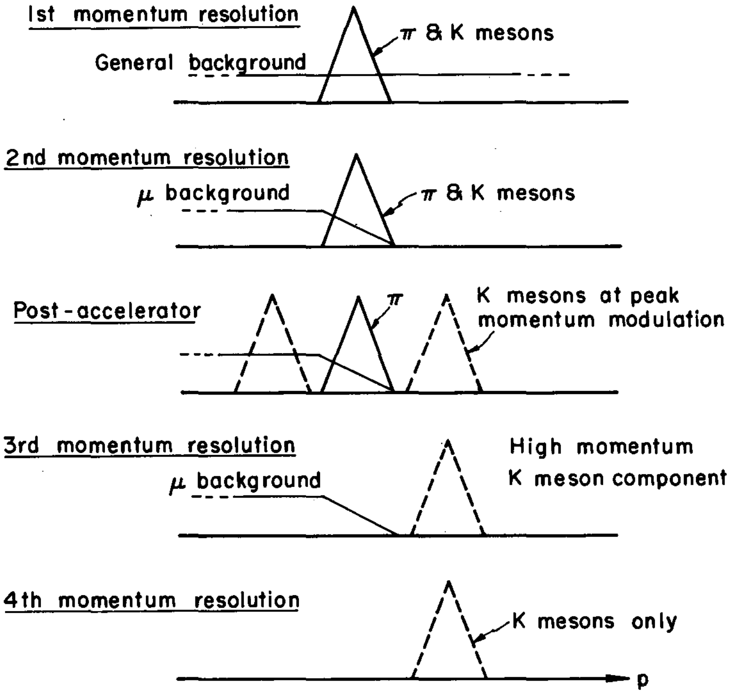

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Fig. 1

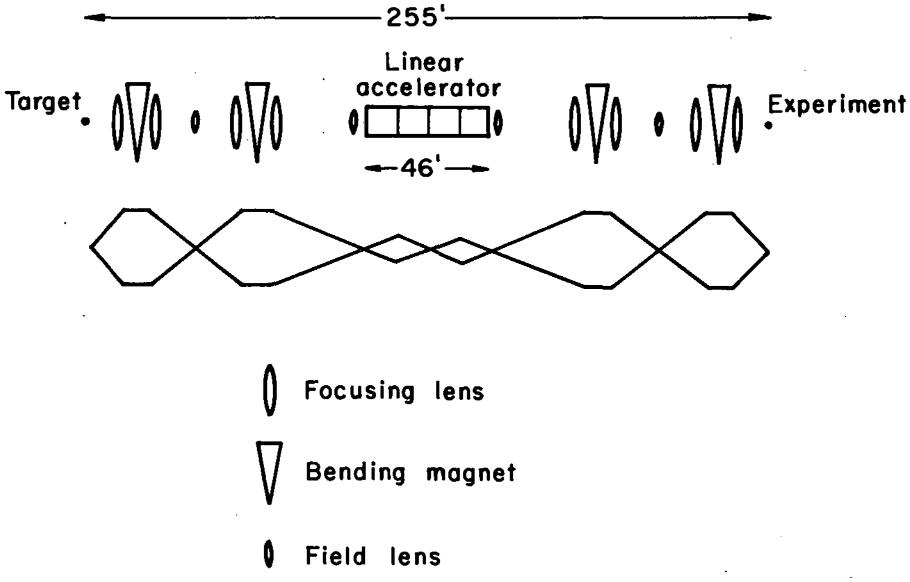

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Fig. 2