THE GENERAL PURPOSE 1 GeV/c SEPARATED BEAM
AT THE ARGONNE ZGS

MASTER

By

Eugene Colton

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operated under contract W-31-109-Eng-38 for the
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Accelerator Research Facilities
October 8, 1975

EC-3

ABSTRACT

Design and operation of the low-momentum beam (42) are discussed. In the normal operating mode, the beam acceptance is calculated to be 21 msr % $\Delta P/P$ at 1 GeV/c. At 0.8 GeV/c, enriched fluxes of 2940 K^- or 16390 K^+ are expected for 10^{11} 12.3 GeV/c incident protons, while 420 $\bar{p}$ are expected at 1 GeV/c. In the reversed-polarity operating mode, the maximum beam acceptance is calculated to be 15.2 msr % $\Delta P/P$; excellent momentum resolution is available in pion and proton beams which are run in this mode. Results on actual beam operation indicate that the beam operates as predicted, with the exception of separator rejection factors.

I. INTRODUCTION

A partially separated low-momentum beam has been constructed at the Argonne ZGS. Beam 42 (as it is called) can transport particles of either charge up to a maximum momentum of 1 GeV/c. The beam was designed to provide enriched high-flux kaon (K) beams up to 0.8 GeV/c and antiproton ($\bar{p}$) beams up to 1.0 GeV/c. The K beams can be used to study KN scattering, stopping K, and hypernuclear spectroscopy¹ experiments; the $\bar{p}$ beams can be utilized to search for $\bar{p}p$ bound states,² or to produce antineutrons ($\bar{n}$).³ The beam can also be used for precision studies using pions (π) and protons (p). A nuclear physics experiment utilizing 0.5 GeV/c π^- has been completed;⁴ a pioneer proton radiography experiment using nearly monoenergetic 200 MeV (0.644 GeV/c) protons was also performed.⁵ In this report we discuss the design and operation of Beam 42.

The broad utility of this beam is realized in two separate modes of operation which are basically identical, except for a reversal of the polarities of the quadrupole magnets: (a) The standard separated mode (normal polarity) emphasizes a large horizontal acceptance with poor momentum resolution, and a tiny vertical acceptance with good mass separation. A 10-foot electrostatic (dc) separator provides a vertical spatial separation between images of undesired and desired particles at the mass collimator. Enriched K and $\bar{p}$ beams are produced in this mode. (b) The unseparated mode (reversed polarity) emphasizes a small horizontal acceptance with excellent momentum resolution, and a large vertical acceptance with potentially poor mass separation. The dc separator can be used to perform some mass separation, if desired. The π and p beams are usually produced in this manner. The detailed beam characteristics for both modes of operation are listed in Tables I and II, respectively.

The operation and first-order matrix optics of Beam 42 are discussed in Section II. Higher-order analyses are presented in Section III: Second-order beam envelopes are given along with the discussion of target length and placement for optimization of flux, separation, and momentum resolution;

some sources of higher-order aberrations are discussed. Second-order Monte-Carlo predictions of normal-polarity beam performance are presented in Section IV: Calculations of solid-angle momentum acceptance, distributions, unseparated and separated fluxes, and muon (μ) contamination are included. A similar, but shorter, analysis of the reversed-polarity mode is given in Section V. Physical measurements made in Beam 42 are compared with the corresponding predictions in Section VI. The concluding statements are contained in Section VII.

II. BEAM OPTICS

A. Physical Elements

The beam line is shown in Fig. 1. The seven quadrupole magnets are labeled rQs or rNQs where r is the bore diameter and s is the length of the pole pieces. The two rectangular bending magnets are labeled rls where r is the pole width, l is the vertical gap, and s is again the length of the pole pieces. All lengths are in inches. The mass and momentum collimator is a 7-inch long (air-filled) rectangular tunnel through a tungsten and brass block; the intermediate foci are centered in the collimator. In operation, the 10-foot separator has crossed electric (E) and magnetic (H) fields. The E field set up across two horizontal plates 4 inches apart deflects charged particles vertically; the H field is adjusted to steer particles of desired mass through the collimator. The nominal E field is 125 kV/in.

B. Beam Operation

Referring to Fig. 1, primary protons are incident from the right upon the target which is placed directly at the entrance to the first quadrupole Q1 (10Q36); thus the central production angle of the secondary beam is 0° . Noninteracting primary protons are translated somewhat by the first bending magnet, B1, and then restored to beam line (not shown) for use in another experiment downstream. In the secondary beam, the quadrupole doublet Q1-Q2, and B1 transport particles of the desired charge and momentum from the target source to a parallel beam in the 10-foot separator in both

the horizontal (x) and vertical (y) planes. The right-handed coordinate system is indicated in Fig. 1; the beam central trajectory propagates in the +z direction. After the separator, the doublet Q3-Q4 brings the beam to a difocus in the collimator center at $z = 384$ in. Separator mass and B1 momentum dispersion permit mass and momentum selection at this point in the y and x planes, respectively.

In the second stage, the beam surviving the collimator is recaptured by the lens Q5 (8NQ16); then B2 and the Q6-Q7 doublet bring the beam to the final difocus which has been nominally chosen 35 inches downstream of the Q7 exit face (at $z = 620$ in.). In the normal-polarity mode, we have chosen the Q5 strength so first-order momentum recombination is obtained at the final difocus. In the reversed-polarity mode, the Q5 strength is adjusted to equate the vertical acceptances of the first and second stages.

C. First-Order Matrix Optics

The beam at location z is represented by the vector T_z with components $x, x', y, y',$ and $\Delta P/P$; x' and y' are the angular divergences dx/dz and dy/dz , respectively, and $\Delta P/P$ is the half-momentum bite for central momentum P . Beam elements are represented by 5×5 matrices, so the beam can be characterized by $T_z = \langle T_z | T_0 \rangle T_0$ in matrix notation. T_0 represents the initial beam produced in the elliptic (cross section) source with semi-axes x_0 and y_0 . The initial phase-space ellipses are assumed erect in the $x_0 x'_0$ and $y_0 y'_0$ planes. For normal polarity, we choose $x_0 = 0.125$ in. and $y_0 = 0.09375$ in.; the numbers are interchanged in the reversed-polarity mode. The beam design was carried out at a transport momentum of 1 GeV/c. The B1 and B2 fields were chosen to bend on-momentum particles symmetrically through 35° and 36° , respectively. The program TRANSPORT⁶ was used to determine the strengths of the quadrupoles Q1-Q7, which satisfy the focal conditions stated in Section II B. The focal conditions are achieved by constraining certain matrix elements; e.g., in the horizontal plane, a focus, parallel or momentum recombination occurs at a zero in the $\langle x | x'_0 \rangle$, $\langle x' | x'_0 \rangle$, or $\langle x | \Delta P/P \rangle$ elements, respectively. The physical beam elements are given in Table III.

The magnetic fields listed were determined in the above analysis; the numbers in parentheses represent the reversed-polarity fields.

The normal-polarity matrix elements are displayed in Fig. 2 together with the optical description of the beam; here focussing lenses are horizontal-focussing quadrupoles with positive magnetic fields (see Table III). The cross marks occur at foci: T $\equiv$ target, fl $\equiv$ intermediate focus, and f2 $\equiv$ final focus. In Fig. 2(c), effective lengths rather than physical lengths are symbolized. At fl, the horizontal ($\langle x|x_0 \rangle$) and vertical ($\langle y|y_0 \rangle$) magnifications are -1.6, and -0.73, respectively. The dispersion parameter $\langle x|\Delta P/P \rangle$ is -0.2 in. /% $\Delta P/P$; thus the momentum resolving power is a poor $0.2/(1.6 \times 0.25) = 0.5/\% \Delta P/P$. At f2, the magnifications $\langle x|x_0 \rangle$ and $\langle y|y_0 \rangle$ are 1.54 and 0.65, respectively. Conspicuous in Fig. 2(a) are the large matrix elements at the position of the Q3-Q4 and Q6-Q7 doublets.

The corresponding reversed-polarity matrix elements and optics are shown in Fig. 3. At fl $\langle x|x_0 \rangle$ and $\langle y|y_0 \rangle$ are -1.11, and -1.10, respectively. The dispersion parameter is -0.98 in. /% $\Delta P/P$; the momentum resolving power is an excellent $0.98/(1.1 \times 0.1875) = 4.7/\% \Delta P/P$. At f2, the magnifications $\langle x|x_0 \rangle$ and $\langle y|y_0 \rangle$ are 1.0 and 0.8, respectively. The final dispersion parameter is -0.12 in. /% $\Delta P/P$. In Fig. 3(b), large matrix elements are observed at the position of the Q3-Q4 and Q6-Q7 doublets. Also noteworthy is the huge dispersion of over 5 in. /% $\Delta P/P$ at the Q6 entrance in Fig. 3(a).

III. HIGHER-ORDER ANALYSIS

A. Normal-Polarity Second-Order Studies

Second-order beam envelopes have been calculated with TRANSPORT for initial beam conditions of $|x'_0| \leq 150$ mr (full width 17.2°), $|y'_0| \leq 8.6$ mr (full width 0.985°), and $|\Delta P/P| \leq 2.0\%$. Horizontal and vertical envelopes are plotted in Figs. 4(a) and 4(b) vs z, respectively, along with the horizontal centroid. The spatial apertures of the elements are crosshatched. The mass and momentum collimator (MC) is open to nominal (see below in

Section IV B). In Fig. 4(a), the dotted curve represents the nominal source placement at 6.0 in. (D1) from the effective entrance to Q1. The large envelopes in the downstream quadrupole doublets are due to first-order effects noted in Section II C. The solid curves appearing in Fig. 4 are drawn for D1 = 7.5 in. The dashed curve in Fig. 4(a) is the resulting horizontal envelope when the source is drawn another 1.5 in. upstream (D1 = 9.0 in.). Horizontal envelopes have also been calculated for downstream source positions; at D1 = 4.5 in. the envelopes diverge to over ± 10 in. at the Q4 entrance, so this direction was not considered further.

Motion of the source upstream causes Q1-Q2 to overfocus horizontally, thereby increasing the horizontal acceptance. In addition, the vertical acceptance is decreased slightly (which aids in mass separation), and the marginal momentum resolution is degraded further. Opposite effects on acceptance are observed for downstream motion of the source. The relative behavior of the different horizontal envelopes in the downstream quadrupole doublets [see Fig. 4(a)] is primarily due to the dependence of the $\langle x|x'_0 \rangle$ matrix element upon D1; e.g., in Q3-Q4 the $\langle x|x'_0 \rangle$ are ~ 30 , 0, and -15 in./rad for D1 values of 6.0, 7.5, and 9.0 in., respectively.

Figure 4 indicates that the target length and z position have sizeable effects upon horizontal acceptance (flux), mass separation, and momentum resolution. A short target centered at D1 = 6.0 in. is preferable for momentum resolution.⁷ However, the important gains in flux and mass separation obtained by increasing target length and D1 warrant centering the target upstream; thus we center the target at D1 = 7.5 in. for the following second-order analysis of the normal-polarity mode. In Fig. 4(a), the second-order horizontal envelopes are converging at the first-order focal locations (f1 and f2). The vertical envelopes are diverging at the corresponding locations in Fig. 4(b). In Table IV A, we list the characteristics of the beam envelopes at f1 and f2. The final conditions can be altered by increasing the Q5 field; this motion will yield $\sim 10\%$ more flux at the expense of a somewhat larger horizontal envelope at f2. Then the entire D1 = 7.5 in. envelopes can be

transmitted through the apertures in Fig. 4; the beam solid-angle acceptance $\pi x'_0 y'_0$ is about 4 msr for $|\Delta P/P| \leq 2.0\%$.

B. Reversed-Polarity Second-Order Studies

Second-order beam envelopes have been calculated with TRANSPORT for initial beam conditions of $|x'_0| \leq 20$ mr (full width 2.3°), $|y'_0| \leq 95$ mr (full width 10.9°) and $|\Delta P/P| \leq 0.5\%$. The horizontal and vertical envelopes (for different D1) are plotted (vs z) in Figs. 5(a) and 5(b), respectively. The horizontal acceptance is limited by Q6. As D1 is increased, the vertical acceptance increases, the horizontal acceptance decreases, and the momentum resolution is degraded. The optimum D1 depends upon beam requirements; D1 = 6.0 in. is best for momentum resolution and mass separation. Maximum flux is obtained with D1 = 9.0 in. As a compromise, we select D1 = 7.5 in. for a normal central source position. The solid curves in Fig. 5 represent D1 = 7.5 in. The second-order horizontal envelope is diverging at f1 and f2. The vertical phase space is an upright ellipse at both foci. The beam envelope characteristics are listed in Table IV B. A slight decrease in Q5 strength allows the full solid envelopes to be transmitted in Fig. 5; the beam acceptance is 6 msr for $|\Delta P/P| \leq 0.5\%$.

C. Higher-Order Aberrations

Higher-order aberrations increase image sizes at focal locations; these effects can be serious if successful operation depends upon maintaining small images in large acceptance beams. In this subsection we consider the vertical image at f1 in normal-polarity operation. The first-order vertical size at f1 is just $2 \langle y | y_0 \rangle y_0$ or 0.14 in. for a 3/16 in. high target. In the second-order treatment, the image size is unchanged for $\Delta P/P = 0$, and is equal to 0.45 in. for $|\Delta P/P| \leq 2.0\%$ (see Table IV A). The increase is due to the second-order chromatic aberration terms $\langle y | y_0 \Delta P/P \rangle (\equiv 0.33 \text{ in. / in.} \cdot \% \Delta P/P)$ and $\langle y | y'_0 \Delta P/P \rangle (\equiv 0.012 \text{ in. / mr} \cdot \% \Delta P/P)$.

Other aberrations can also increase the vertical size at f1. Ray tracing or a proper third-order theory can illuminate effects due to non-paraxial rays in ideal magnets. We consider, however, geometric aberrations which

are caused by imperfections in the first-stage magnets. Specifically, we treat two cases: (i) non-uniformity of $\int \vec{H} \cdot d\vec{l}$ with x in B1, and (ii) non-uniformity of gradient with x (spherical aberrations) of Q1-Q4. The first case has been considered by Good⁸ and can be directly treated as a sextupole term in TRANSPORT if the field behavior in B1 is represented by

$$\frac{H_x - H_o}{H_o} = \epsilon x^2 \quad (3.1)$$

where H_o is the central field. B1 approximately exhibits this behavior with $\epsilon = -0.0002$ at 0.7-0.8 GeV/c and ϵ close to -0.0005 at 1.0 GeV/c. The program TRANSPORT was run for ϵ values of 0, -0.0002 , -0.0005 , and -0.0007 in B1; the corresponding second-order full vertical envelope sizes at f1 were 0.45 in., 0.56 in., 0.90 in., and 1.20 in., respectively. These results indicate increased spot size (and decreased mass separation) with momentum. Experimental shimming of B1 to reduce ϵ to zero could solve the problem.

The third-order spherical aberrations of Q1-Q4 can be treated as perturbations to the vertical beam divergence $\Delta y'$ and focal length $\Delta(1/f_y)$; the perturbations are propagated upstream to the target to produce a source broadening

$$\Delta y_o = \langle y | y'_o \rangle y \Delta \left(\frac{1}{f_y} \right) \quad (3.2)$$

where y is evaluated at the aberration (quadrupole center). Determination of $\Delta(1/f_y)$ from measured wire-orbit data permits evaluation of Δy_o . Since measurements of f_y are non-existent, we express⁹ f_y in terms of measured horizontal focal lengths $f_x(x)$

$$\Delta \left(\frac{1}{f_y} \right) = C \left[\Delta \left(\frac{1}{f_x} \right) + \frac{d}{dx} \Delta \left(\frac{1}{f_x} \right) \right] \quad (3.3)$$

Eq. (3.3) is valid for x and y constant through each magnet, a poor assumption in Q1. The coefficient C is the transformation from wire-orbit momentum P_w and magnet current I_w to the beam conditions P and I [$C = P_w I / (P I_w)$]. The differential $\Delta(1/f_x) = \Delta f_x(x) / f_x^2$ where $\Delta f_x(x) = f_x(x) - f_x(0)$.

Measurements of f_x are taken from The Magnets and Targetry Handbook.¹⁰ Then the $\Delta f_x(x)$ are empirically fitted to αx^N ; the Δy_0 are obtained using Eqs. (3.2) and (3.3). If one assumes $x_0 = y_0 = 0$, then the circle of least confusion is given by

$$\Delta y_0 = \frac{Ca(N+1)}{2 f_x^2} y_0' <y|y_0'>^2 (<x|x_0'>x_0')^N. \quad (3.4)$$

The Δy_0 are listed in Table V along with the other quantities for $x_0' = 150$ mr and $y_0' = 8.6$ mr. The matrix elements refer to the magnet centers for a source at $D1 = 6.0$ in. (as in Fig. 2). The Δy_0 entries in parentheses were calculated for the source at $D1 = 7.5$ in. The Δy_0 aberrations for Q1, Q2, and Q4 are all less than one-half target height (small). For Q3, however, the half-aberration Δy_0 is nearly one target height for $D1 = 6.0$ in. (a serious aberration); even if the target is actually centered at $D1 = 7.5$ in., rays coming from the downstream end will be badly aberrated in Q3-Q4. Better quality magnets could cure this problem.

IV. NORMAL-POLARITY PREDICTIONS

A. Method

The system was evaluated to second order using the Monte-Carlo program DECAY TURTLE.¹¹ The production target was 3 inches long, of elliptical cross section, and centered at $D1 = 7.5$ in. The initial beam conditions were $|x_0| \leq 0.125$ in., $|y_0| \leq 0.09375$ in., $|x_0'| \leq 220$ mr, $|y_0'| \leq 12.5$ mr, and $|\Delta P/P| \leq 9.0\%$. Effects due to fringe focussing and spherical aberrations of quadrupole magnets were neglected. However, the sextupole component ϵx^2 [see Eq. (3.1)] was included in the B1 field. No

sextupole term was included for B2 since the magnet was shimmed to give $|\epsilon| < 0.0001$ for $0.7 < P < 1.0$ GeV/c. Studies were performed using four ϵ values for B1. Twenty-thousand (20000) rays were started in the target and tracked through the system in order to study collimation and beam distributions. Quantitative evaluation of beam fluxes and separator rejection factors used 50000 starting rays. The expected beam performance is explained below in subsections B-D.

B. Solid-Angle Momentum Acceptance

Twenty-thousand rays were started in the target and tracked through the system. The solid angle momentum acceptance is

$$\Delta\Omega \frac{\Delta P}{P} = \pi \cdot 220 \text{ mr} \cdot 12.5 \text{ mr} \cdot 18\% \frac{\Delta P}{P} * \frac{N}{20000} \quad (4.1)$$

where N is the number of rays reaching the beam end at $z = 620$ in. without striking an aperture or collimator. Two values of N were determined for each ϵ value for B1, corresponding to two settings for the mass and momentum collimator (MC). In the first case, the MC was wide open, while in the second, the MC jaws were set to nominal as in Fig. 4. These openings are: horizontal upstream $-0.9 \text{ in.} < x < 0.7 \text{ in.}$, horizontal downstream $-0.7 \text{ in.} < x < 0.5 \text{ in.}$, and vertical $|y| < 0.25 \text{ in.}$ Equation (4.1) was used to calculate the $\Delta\Omega \Delta P/P$; they are listed in Table VI. The beam is capable of transmitting a maximum of 25-27 msr % $\Delta P/P$ under wide open conditions. Closing down the MC jaws to nominal reduces the acceptance by 10-20%. In particular, we observe $\Delta\Omega \Delta P/P$ values of 23 msr % $\Delta P/P$ for $0.7 \leq P \leq 0.8$ GeV/c, and about 20 msr % $\Delta P/P$ near 1.0 GeV/c. In the subsections which follow, the MC jaws are closed to nominal.

C. Beam Distributions

In this subsection, we show the DECAY TURTLE distributions for 20000 rays started, and with $\epsilon = 0$ in B1. Corresponding distributions for $-0.0007 \leq \epsilon < 0$ are nearly identical, with the exception of the vertical image at f1. The Monte-Carlo distributions of x'_0 , y'_0 , and $\Delta P/P$ are plotted in

Fig. 6 for the 3136 rays which successfully reach the beam end at $z = 620$ in. (f2). The rms half-widths (σ) for these distributions are 95.0 mr, 5.0 mr, and 1.7%, respectively. The distributions of x , y , and $\Delta P/P$ for the 3979 rays reaching the entrance face of the collimator (MC) are shown in Fig. 7; the σ values for these distributions are 0.48 in., 0.12 in., and 2.2%, respectively. The solid curve superimposed upon the y distribution in Fig. 7(b) is the normalized prediction assuming $\epsilon = -0.0005$ for B1; its σ value is 0.17 in. The corresponding σ for the $\epsilon = -0.0002$ and -0.0007 vertical distributions are 0.13 in. and 0.20 in., respectively. The vertical dashed lines in Figs. 7(a) and 7(b) represent the nominal horizontal and vertical openings at the entrance to the MC. At f2, 89% of the beam is confined to the 1-inch square with -0.4 in. $< x < 0.6$ in. and $|y| < 0.5$ in. The Monte-Carlo projections of x , x' , y , and y' (at f2) are displayed in Fig. 8; the σ values for these distributions are 0.3 in., 50 mr, 0.21 in., and 10 mr, respectively.

D. Particle Yields and Separation

In this subsection we calculate the unseparated yields of particles expected at beam end (f2) for a 3-inch copper production target. Then separator operation is studied at 0.8 and 1.0 GeV/c; these are the maximum usable momenta for adequately enriched K and $\bar{p}$ beams, respectively. The yield of particles expected at f2 is given by

$$Y = r_1 \cdot \frac{d^2 N(0^\circ)}{d\Omega dP} \cdot \left(\Delta\Omega \frac{\Delta P}{P} \right) P \cdot r_2 \cdot \alpha \cdot \text{flux} \quad (4.2)$$

where α is the targetting efficiency, flux is the number of incident primary protons and $d^2 N(0^\circ)/d\Omega dP$ is the number of particles produced at 0° from the target by primary protons of momenta P_0 , in the desired solid angle band per incident proton. The correction r_1 results from integrating $d^2 N(x'_0)/d\Omega dP$ over the predicted x'_0 distribution [see Fig. 6(a)]. The factor $r_2 \equiv \exp(-620/L_0)$ is the decay survival fraction at f2 for unstable particles of mass m and decay length $L_0 = Pc\tau/m$ (in inches).

Using Eq. (4.2) we calculate yields at f2 for $e^\pm$, $\pi^\pm$, $K^\pm$, and $p^\pm$; the results are displayed in Fig. 9 for $0.4 \leq P \leq 1.0$ GeV/c. We assume $\alpha = 0.7$ and a flux of 10^{11} protons with $P_0 = 12.33$ GeV/c. The r_1 were evaluated from the data of Davies et al.¹² and Marmer et al.¹³; typical values range from 1.0-1.3. The $d^2N(0^\circ)/d\Omega dP$ were obtained from Ref. 13, and the $\Delta\Omega\Delta P/P$ estimated from Table VI. The $c\tau$ values were ∞ , 307.2 in., 146.0 in., and ∞ for e , π , K , and p , respectively.¹⁴ Muons from $\pi \rightarrow \mu \nu$ decays are also present in the beam at f2; the DECAY TURTLE predictions of μ/π are $\sim 10\%$ at 0.7-0.8 GeV/c and 8% at 1.0 GeV/c. In Table VII, we tabulate the predicted beam fluxes at 0.8 and 1.0 GeV/c. At 0.8 GeV/c, the ratios of $(e\pi\mu)/K$ are ~ 317 and ~ 1920 for positive and negative charged beams, respectively. The $(e^-\pi^-\mu^-)/\bar{p}$ ratio is about 12450 at 1.0 GeV/c.

The unseparated ratios can be reduced to provide enriched K and $\bar{p}$ beams by operation of the dc separator. Following Colton⁹ we treat the separator as a vertical bending magnet in DECAY TURTLE. The deflecting E field is assumed 125 kV/in.; the crossed H field steers the desired particles undeflected through the beam line. At f1, the centroid of specified undesired particles (not μ) is displaced to $y_c(\text{in.}) = -0.1625 q \Delta y'$ where $\Delta y'$ is the angular deflection experienced in the separator (in mr);¹⁵ the MC removes most of the undesired particles. The separation-to-image size at f1 is $|y_c|/2\sigma$ where σ refers to the distribution in Fig. 7(b).¹⁶ The program DECAY TURTLE was run with separator deflection at 0.8 GeV/c (K undeflected) and 1.0 GeV/c ($\bar{p}$ undeflected). The separator rejection factors (SRF) and $|y_c|/2\sigma$ are presented in Table VIII. The predicted separated yields at 0.8 GeV/c for 10^{11} protons incident are 16390 K^+ with $(e^+\pi^+\mu^+)/K^+ \approx 10$, and 2940 K^- with $(e^-\pi^-\mu^-)/K^- \approx 55$. At 1.0 GeV/c, the corresponding results are 420 $\bar{p}$ with $(e^-\pi^-\mu^-)/\bar{p} \approx 60 \pm 12$.¹⁷

V. REVERSED-POLARITY PREDICTIONS

As in Section IV, the system was evaluated to second order using the Monte-Carlo program DECAY TURTLE.¹¹ Twenty-thousand rays were started in a 3-inch long production target centered at $D1 = 7.5$ in. The

initial beam conditions were $|x_0| \leq 0.09375$ in., $|y_0| \leq 0.125$ in., $|x'_0| \leq 30$ mr, $|y'_0| \leq 200$ mr, and $|\Delta P/P| \leq 2.5\%$. Aberrations of magnets were neglected. Initially the MC jaws were adjusted to pass rays with $|x| \leq 1.50$ in., and $|y| \leq 0.5$ in. at the f1 location. This configuration transmits the maximum number of rays (3230) to the beam end at f2;¹⁸ the corresponding solid-angle momentum acceptance is calculated to be 15.2 msr % $\Delta P/P$.

In Fig. 10 we present the Monte-Carlo spectra of x'_0 , y'_0 , and $\Delta P/P$ for the 3230 surviving rays. The rms half-widths (σ) for these distributions are 13.4 mr, 63.6 mr, and 0.66%, respectively. The momentum resolution capability of the system is depicted in Fig. 11(a) as the band of $\Delta P/P$ vs x at the entrance to the MC. The y distribution at the MC is shown in Fig. 11(b) for 9960 incident rays; its σ value is 0.23 in.¹⁹ The vertical dashed lines in Fig. 11 show the MC openings used. The final x , x' , y , and y' (at f2) are displayed in Figs. 12(a) - 12(d), respectively. The σ values for these distributions are 0.09 in., 14 mr, 0.12 in., and 38 mr, respectively; the x and y distributions are significantly narrower than the corresponding normal-polarity spectra ($\sigma_x = 0.3$ in. and $\sigma_y = 0.21$ in.). In this idealized situation, about 95% of the beam passes through a 0.5 in. diameter circle at f2.

The pion and proton beam fluxes expected at f2 are plotted in Fig. 13 as a function of momentum. The yields were obtained using Eq. (4.2) and assume the full acceptance of 15.2 msr % $\Delta P/P$. The primary flux was 10^{11} protons incident upon a 3-inch copper target with 70% targetting efficiency. Beam enrichment can be obtained by running with the dc separator on. For an E field of 125 kV/inch, the centroid of specified undesired particles (at f1) is displaced to $y_c = -0.03 q \Delta y'$ relative to the undeflected desired particles, where $\Delta y'$ is the angular deflection experienced in the separator (in mr).¹⁵ The separation to image size at f1 ($|y_c|/2\sigma$) is then $|y_c|/0.46$; this ratio should be greater than one for practical enrichment. Thus the maximum momenta for useful πe and πp separation are 0.2 GeV/c and 0.7 GeV/c, respectively. The vertical opening at the MC should be reduced to, e.g., ± 0.25 in. if mass separation is performed.

Beam momentum spread is controlled by horizontal collimation at f1 [see Fig. 11(a)]. The Monte-Carlo program was run with six settings of the MC opening. In Table IX we list the respective transmissions and momentum bites at f2; the vertical opening at f1 was ± 0.5 in. For the smallest horizontal opening used (± 0.25 in.) the transmitted flux drops to 25% of maximum, and the σ of the $\Delta P/P$ distribution is only 0.15%. When the realistic sextupole component [see Eq. (3.1)] is included in the B1 field, the band in Fig. 11(a) is observed to spread with decreasing ϵ . Thus the momentum resolution capability of the system degenerates with increasing current in B1 (and increasing momentum). In addition, the x distribution at f2 [Fig. 12(a)] is broadened to, e.g., $\sigma = 0.13$ in. and 0.22 in. for ϵ values of -0.0002 and -0.0005, respectively.

VI. MEASUREMENTS

A. Normal-Polarity Operation

Three yield measurements have been performed in the normal-polarity mode: Separated fluxes of 0.2 GeV/c π^- , 0.43 GeV/c K^- , and 1.0 GeV/c $\bar{p}$ have been measured. In each case, a 3-inch long copper production target was used. Primary proton momentum was 12.3 GeV/c. The beam length was 650 in. instead of the nominal 620 in., and the MC jaws were open to nominal (see Sec. IV. B). The separator was operated at a field of 125 kV/in. Counting and particle identification were accomplished with scintillation and Cerenkov counters and time-of-flight techniques. Beam sizes were measured using proportional chambers; the observed images at the MC and beam end agreed with the DECAY TURTLE predicted sizes (see Section IV C).

(i) At 0.2 GeV/c, the unseparated beam was found to be 95% e^- . The beam was purified to 75% $\pi^- \mu^-$ using the separator; this corresponds to a separator rejection factor (SRF) of 52. The separated flux was found to be $4200 \pi^- \mu^- / 10^{11}$ incident protons.

(ii) At 0.43 GeV/c, the unseparated beam end ratios of e^-/K^- and $\pi^- \mu^-/K^-$ were found to be 58000 and 15500, respectively. These ratios were

reduced to 254 and 312, respectively, when the separator was tuned for K^- . The SRF values are then ~ 230 for e^- , and 50 for $\pi^-\mu^-$; the total SRF for $e^-\pi^-\mu^-$ is 130. The separated flux was found to be $37 K^-/10^{11}$ incident protons, in good agreement with the predicted number of 35 K^- .

(iii) At 1.0 GeV/c, the separated ratio of $(e^-\pi^-\mu^-)/\bar{p}$ was found to be 175; our prediction was 60 ± 12 (see Section IV.D). In addition, the separated flux was measured to be $250 \bar{p}/10^{11}$ incident protons; the expected value was about 420 ± 80 .

B. Reversed-Polarity Operation

The beam has been tuned for 0.644 GeV/c protons; this momentum corresponds to 0.2 GeV kinetic energy protons. The conditions for beam operation were the same as those used in the normal-polarity operation, with the exception of the MC jaws; here the vertical opening of the MC was $|y| \leq 0.3125$ in. The horizontal opening was varied to study momentum resolution. Initially, the beam was transported unseparated with the MC jaws open to pass particles with $|x| \leq 0.5$ in. The measured flux was 860000 particles/ 10^{11} protons incident; the expected flux was 930000/ 10^{11} protons incident. When the separator was tuned for protons, the observed SRF values were 30 for e^+ and 10 for $\pi^+\mu^+$; the corresponding predicted values were 55 and 50, respectively. Momentum resolution has been determined using differential range techniques. The observed σ values for the $\Delta P/P$ are generally twice the predicted value for a perfectly tuned beam. Of course, no attempt was actually made to tune the beam for minimum momentum spread.

VII. CONCLUSIONS

The observed behavior of the beam is in agreement with the design predictions, with the exception of the separation rejection factors (SRF). The design specifications for normal-polarity and reverse-polarity beam operation are detailed in Tables I and II, respectively. The experimental fluxes and distributions are well described by the first- and second-order matrix treatment of the beam. The low SRF are mainly encountered with π/μ contaminants, and to a lesser degree with electrons.

In principle, one should see nearly the same SRF for e and π produced in the production target. The predicted SRF will be higher than the observed value because of approximations in the analysis, as well as neglect of phenomena such as scattering of particles off the separator plates, and the serious spherical aberrations in Q3-Q4 (see Section III C). Another source of pions arises from hadron decay near the target; processes such as $\Lambda^0 \rightarrow p\pi^-$, $K_S \rightarrow \pi^+\pi^-$, etc., contribute. These pions appear to emanate from a large diffuse source at the production target location. The SRF for these pions is small.

The SRF of the beam can be improved with use of higher quality magnets for B1, Q3, and Q4. Furthermore, higher K fluxes could be obtained if the Q3-Q4 doublet was replaced by a symmetric triplet Q3-Q5 utilizing 8NQ16's (polarities HF, VF, HF). The second stage of the beam would be B2-Q6-Q7. Overall beam length could be cut to 530 in., perhaps, thereby insuring higher kaon fluxes. If one desires increased $\bar{p}$ fluxes and better SRF values, then one should go to a two-stage separated beam.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. I. Spirn for performing the initial beam design. In addition, the help of Drs. E. W. Hoffman, R. D. Klem, and D. R. Moffett is appreciated. The assistance of those involved in measuring the yields is also acknowledged. Finally, thanks go to the numerous technicians, riggers, surveyors, draftsmen, engineers, and other support personnel who transformed the beam design into an operational facility.

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15. $\Delta y' = 14.5/P_c [1/\beta_U - 1/\beta_D]$ where P_c is the momentum in GeV, and β_U and β_D are the velocities for undesired, and desired particles, respectively.
16. The vertical image size at f1 is increased slightly due to the momentum aberration of the electrostatic separator.
17. This purity is quickly degraded if the ϵ parameter for B1 is decreased slightly; e.g., for $\epsilon = -0.0007$ we find $(e^-\pi^-\mu^-)/\bar{p} = 100 \pm 11$.
18. Larger collimator openings will not increase the transmission to f2.
19. The actual y distribution expected at f1 is broader since rays with $|\Delta P/P| > 2.5\%$ are successfully transmitted to f1.

Table I. Normal-Polarity Beam Characteristics

1. Momentum range: 0-1.0 GeV/c positives or negatives.
2. Nominal target: 1/4 in. x 3/16 in. x 3 in. copper
3. Central production angle: 0°
4. Nominal beam length: 620 in.
5. Beam solid angle acceptance: 4 msr for $|\Delta P/P| \leq 2.0\%$
6. Integrated solid-angle momentum acceptance at 1.0 GeV/c: 21 msr % $\Delta P/P$
7. Separator: 10 ft with 4 in. vertical gap
8. $\Delta P/P$ bite transmitted: $\sigma = 1.7\%$
9. First-order $\frac{\text{dispersion}}{\text{image size}}$ at momentum collimator: 0.5 for 1% $\Delta P/P$
10. Separation to image size ($|y_c|/2\sigma$) at mass slit center for separator
E field of 125 kV/in.:

0.8 GeV/c	πK	0.45/0.25 (≈ 1.8)
1.0 GeV/c	πp	0.575/0.25 (≈ 2.3)

11. Beam end characteristics for a 620 in. beam.
First-order horizontal magnification: 1.54
First-order vertical magnification: 0.65
Second-order horizontal projection: $2\sigma = 0.6$ in.
Second-order vertical projection: $2\sigma = 0.42$ in.
Second-order horizontal divergence: $2\sigma = 100$ mr
Second-order vertical divergence: $2\sigma = 20$ mr
12. Unseparated yields expected at beam end for 10^{11} 12.3 GeV/c protons
incident with 70% targetting efficiency

0.8 GeV/c	$K^+/K^-/\bar{p} \equiv 16440/2950/230$
1.0 GeV/c	$K^+/K^-/\bar{p} \equiv 30740/5980/425$

13. Predicted beam purity with separator field at 125 kV/in. and mass
slit nominal:

0.8 GeV/c	$e^+\pi^+\mu^+/K^+ = 10, e^-\pi^-\mu^-/K^- = 55$
1.0 GeV/c	$e^-\pi^-\mu^-/\bar{p} = 60 \pm 12$

Table II. Reversed-Polarity Beam Characteristics

1. Momentum range: 0-1.0 GeV/c positives or negatives
2. Nominal target: 3/16 in. x 1/4 in. x 3 in. copper
3. Central production angle: 0°
4. Nominal beam length: 620 in.
5. Beam solid angle acceptance: 6 msr for $|\Delta P/P| \leq 0.5\%$
6. Maximum integrated solid-angle momentum acceptance:
15.2 msr % $\Delta P/P$
7. Separator: 10 ft with 4 in. vertical gap
8. Maximum $\Delta P/P$ bite transmitted: $\sigma = 0.65\%$
9. First order $\frac{\text{dispersion}}{\text{image size}}$ at momentum collimator: 4.7 for 1% $\Delta P/P$
10. Separation to image size ($|y_c|/2\sigma$) at mass slit center for separator
E field of 125 kV/in.:

1.0 GeV/c	πp	0.166/0.46	($\equiv 0.36$)
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11. Beam end characteristics for a 620 in. beam
 First-order horizontal magnification: 1.0
 First-order vertical magnification: 0.8
 Second-order horizontal projection: $2\sigma = 0.18$ in.
 Second-order vertical projection: $2\sigma = 0.24$ in.
 Second-order horizontal divergence: $2\sigma = 28$ mr
 Second-order vertical divergence: $2\sigma = 76$ mr
12. Maximum unseparated 1 GeV/c yields expected for 10^{11} 12.3 GeV/c
 protons incident with 70% targetting efficiency

$$\pi/p = 1.8 \times 10^6 / 2.1 \times 10^6$$

Table III. Beam 42 Elements

<u>Element</u>	<u>Effective Length (inches)</u>	<u>Field at Pole (kG)</u>
*Target 1/4 in. w x 3/16 in. h	3.0	
Drift	6.0	
Quadrupole Q1 10Q36	38.0	+11.014 (-11.524)
Drift	11.2	
Quadrupole Q2 8NQ16	19.6	-3.033 (+6.592)
Drift	17.55	
Bend B1 30VI36H	41.3	19.41 (35° bend)
Drift	23.35	
DC Separator	116.0	
Drift	13.95	
Quadrupole Q3 10Q18	19.3	-7.292 (+7.292)
Drift	13.5	
Quadrupole Q4 10Q18	19.3	+11.891 (-11.891)
Drift	42.0	
Collimator	7.0	
Drift	17.2	
Quadrupole Q5 8NQ16	19.6	+9.773 (-7.5)
Drift	19.16	
Bend B2 20VIII42C	48.2	17.107 (36° bend)
Drift	18.25	
Quadrupole Q6 10Q18	19.3	-8.837 (+10.068)
Drift	11.95	
Quadrupole Q7 10Q36	38.0	6.372 (-6.541)
Drift	40.0	

*For normal polarity. In the reversed mode, the target is 3/16 in. w x 1/4 in. h.

Table IV. A. Normal-Polarity Second-Order Beam

Characteristics for D1 = 7.5 Inches

<u>Quantity</u>	<u>Focal Location</u>	
	<u>f1</u>	<u>f2</u>
Horizontal centroid	-0.1 in.	+0.24 in.
Vertical centroid	0	0
Horizontal beam width	1.14 in.	1.10 in.
Horizontal divergence	± 94 mr	± 121 mr
Vertical beam width	0.46 in.	1.04 in.
Vertical divergence	± 13 mr	± 21 mr

Table IV. B. Reversed-Polarity Second-Order Beam

Characteristics for D1 = 7.5 Inches

<u>Quantity</u>	<u>Focal Location</u>	
	<u>f1</u>	<u>f2</u>
Horizontal centroid	0	0.18 in.
Vertical centroid	0	0
Horizontal beam width	1.02 in.	0.56 in.
Horizontal divergence	± 20 mr	± 29 mr
Vertical beam width	0.42 in.	0.32 in.
Vertical divergence	± 57 mr	± 82 mr

Table V. Spherical Aberration Results for Q1-Q4 in the

Normal-Polarity Mode, $x'_0 = 150$ mr,

$y'_0 = 8.6$ mr, and $D1 = 6.0$ Inches

Quantity	Magnet			
	Q1	Q2	Q3	Q4
C	8.73	1.626	3.425	6.81
α (inch)	1.015×10^{-2}	6.36×10^{-3}	1.125	8.06×10^{-5}
N	3.3	2.87	1.016	6.314
f_x (inch)	141.9	76.3	152.5	163.8
$\langle y y'_0 \rangle$ (inch)	38.1	127.1	191.5	87.1
$\langle x x'_0 \rangle$ (inch)	15.3	20.8	21.8	29.0
Δy_0 (inch)	.0018 (.0024)	.0125 (.0144)	.175 (.009)	.053 (.0018)

*Values in parentheses were calculated with $D1 = 7.5$ in.

Table VI. Normal-Polarity Solid-Angle Momentum

Acceptances for Different Values of ϵ

(See Section IV. B)

ϵ (inch ⁻²)	MC Open	MC Nominal
0	26.6 msr % $\Delta P/P$	24.0 msr % $\Delta P/P$
-0.0002	26.0 msr % $\Delta P/P$	23.3 msr % $\Delta P/P$
-0.0005	24.8 msr % $\Delta P/P$	20.9 msr % $\Delta P/P$
-0.0007	23.8 msr % $\Delta P/P$	19.2 msr % $\Delta P/P$

Table VII. Unseparated Yields at f2 for 10^{11} 12.3 GeV/c Protons
Incident Upon a Three-Inch Copper Target

Particle	Yields	
	0.8 GeV/c	1.0 GeV/c
e^+/e^-	$2.8 \times 10^6 / 3.0 \times 10^6$	$2.6 \times 10^6 / 2.7 \times 10^6$
π^+/π^-	$2.2 \times 10^6 / 2.4 \times 10^6$	$2.4 \times 10^6 / 2.4 \times 10^6$
μ^+/μ^-	$0.22 \times 10^6 / 0.24 \times 10^6$	$0.19 \times 10^6 / 0.19 \times 10^6$
K^+/K^-	16440/2950	30740/5980
$p/\bar{p}$	$2.9 \times 10^6 / 230 \pm 110$	$2.8 \times 10^6 / 425 \pm 80$

Table VIII. Separator Rejection Factors (SRF) at f2 and $|y_c|/2\sigma$
at f1 for Separator Field of 125 kV/inch

Particle	0.8 GeV/c		1.0 GeV/c	
	SRF	$ y_c /2\sigma$	SRF	$ y_c /2\sigma$
e	59 ± 5	2.0	400 ± 80	2.3
π	26 ± 2	1.8	350 ± 70	2.3
μ	16 ± 3	-	24 ± 6	-
K	1.003	0	-	-
$\bar{p}$	-	-	1.01	0

Table IX. Reversed-Polarity Beam Performance as a
Function of MC Horizontal Opening

x (inches)	$\Delta\Omega \frac{\Delta P}{P} \left(\text{msr } \% \frac{\Delta P}{P} \right)$	$\sigma \Delta P / P$ (%)	Total $\Delta P / P$ Bite (%)
± 0.25	4.0	0.15	± 0.4
± 0.50	8.0	0.29	± 0.6
± 0.75	11.1	0.42	± 0.9
± 1.00	13.3	0.53	± 1.1
± 1.25	14.9	0.63	± 1.4
± 1.50	15.2	0.66	± 1.6

FIGURE CAPTIONS

Figure 1. Experimental beam layout. The xyz coordinate system has beam propagating in the +z direction.

Figure 2. (a) Normal-polarity first-order horizontal plane matrix elements vs z.

(b) Normal-polarity first-order vertical plane matrix elements vs z.

(c) Optical layout of the normal-polarity beam design. The x's represent first-order focal locations; converging lenses are horizontally focussing.

Figure 3. (a) Reverse-polarity first-order horizontal plane matrix elements.

(b) Reverse-polarity first-order vertical plane matrix elements.

(c) Optical layout of the reverse-polarity beam design. The x's represent first-order focal locations; converging lenses are horizontally focussing.

Figure 4. Normal-polarity second-order transport half envelopes for a source 0.25 in. wide and 0.1875 in. high, and with initial conditions $|x'_0| \leq 150$ mr, $|y'_0| \leq 8.6$ mr, and $|\Delta P/P| \leq 2\%$. The collimators and apertures are cross-hatched.

(a) Horizontal plane behavior for three different values for the first drift length. The centroid is also displayed.

(b) Vertical plane behavior for $D1 = 7.5$ in.

Figure 5. Reverse-polarity second order transport half envelopes for a source 0.1875 in. wide and 0.25 in. high, and with initial conditions $|x'_0| \leq 20$ mr, $|y'_0| \leq 95$ mr, and $|\Delta P/P| \leq 0.5\%$. The collimators and apertures are shown cross-hatched.

(a) Horizontal plane behavior for $D1 = 7.5$ in.

(b) Vertical plane behavior for the three denoted values for D1.

Figure 6. Normal-polarity DECAY TURTLE distributions of the initial x'_0 , y'_0 , and $\Delta P/P$ for the 3136 undeflected rays reaching the final focus f2.

Figure 7. Normal-polarity DECAY TURTLE distributions of x , y , and $\Delta P/P$ at the upstream face of the MC for 3979 rays. The dashed lines represent nominal slit openings. The solid curve in (b) is the normalized prediction assuming $\epsilon = -0.0005$ for B1 (see Sec. IV C).

Figure 8. Normal-polarity DECAY TURTLE distributions of x , x' , y , y' at the final focus f2 for 3136 rays.

Figure 9. Normal-polarity unseparated yields of $e^\pm$, $\pi^\pm$, $K^\pm$, $p^\pm$ expected at f2 for 10^{11} protons incident with 70% targetting efficiency and momentum 12.3 GeV/c. The target is 3 in. copper.

Figure 10. Reverse-polarity DECAY TURTLE distributions of the initial x'_0 , y'_0 , and $\Delta P/P$ for 3230 undeflected rays reaching f2.

Figure 11. (a) Reverse-polarity momentum resolution capacity of the system at the momentum collimator.

(b) Reverse-polarity DECAY TURTLE y distribution at the MC for 9960 rays; the dashed lines show nominal openings.

Figure 12. Reverse-polarity DECAY TURTLE distributions of x , x' , y , and y' at f2 for 3230 rays.

Figure 13. Reverse-polarity unseparated maximum yields of $\pi^\pm$ and p expected at f2 for 10^{11} protons incident with 70% targetting efficiency and momentum 12.3 GeV/c. The target is 3-inch copper.

BEAM 42
Enriched Stopping K

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

Figure 13.