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LOW ENERGY SEPARATED BEAM AT THE C.E.R.N. P.S.

by

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I. Design Considerations

The electrostatically separated beam described in this report was designed to provide particles for the following experiments:

- 1) K^+ and K^- at 800 MeV/c, for heavy liquid chamber experiments;
- 2) K^+ stopping in a heavy liquid chamber;
- 3) K^- stopping in liquid hydrogen, and in emulsion.

The possibility of operation as a beam of $\bar{p}$ stopping in hydrogen was also to be investigated.

Requirement 3) is the most stringent, therefore an attempt was made to maximize the number of K^- stopping in ~ 35 cm. of liquid hydrogen. (See Table I). In a beam of practical length it is necessary to transport the K^- at an energy where the decay loss is not too great, then to degrade the energy to the correct value for stopping in the liquid hydrogen just before the bubble chamber. The optimum transport momentum can be estimated, taking into account the variation in target flux, the loss due to decay, and the loss due to interaction, multiple scattering, and straggling in a copper degrader. The results of such an estimate are shown in Figure 1, for beam lengths of 18 and 25 meters, and for a K^- flux proportional to p_K as well as p_K^2 , forms suggested by measurements of the K^- flux at 15° to an internal proton beam of 19 GeV/c.¹ We concluded that a beam momentum of 800 MeV/c would be near the optimum for the stopping K^- while at the same time fulfilling the requirements of the other experiments. The choice of a fixed value of momentum permitted the fixed shimming of the magnets described later.

Although our knowledge of the angular dependence of the flux of slow K^- is very limited, the data of Table I seem to indicate an appreciable angular dependence. By the use of a special magnet which will be described later, we have been able to take particles at 15° while maintaining a large solid angle, with the target in a short (1.1 m) straight section.

We have adopted a beam design utilizing two stages of electrostatic separation in a beam of ~ 23 m. to the second main slit. A single stage design would require a momentum and image defining section prior to the separator stage in order to reject the $\sim 30,000 \pi^-$ which must be admitted to obtain one stopped K^- . Such a design would not result in a much shorter beam.

II. Beam Optics and Elements

To provide sufficient intensity, a slow K beam must have the following properties: short length, large solid angle, and small vertical images for adequate separation. The ratio of separation to target image size is greatest for a beam traversing the separators parallel to the plates. Our design reflects this consideration as well as the limitation imposed by the availability of only four short quadrupoles.

Figure 2 shows the design evolved to satisfy these conditions. Table II gives the important parameters of the beam. The number of quadrupoles used has been kept to a minimum by use of vertical edge focusing(4) in the two one-meter bending magnets. This focusing is extremely valuable since there is not an equal defocusing in the horizontal plane, a circumstance which tends to increase the effective aperture of the system. It will be noticed that only one doublet is used in the whole system, at the end, and that no horizontal focusing is needed near the first mass slit.

The behavior of the off momentum rays is shown in Figure 3. The importance of the large momentum dispersion at the first mass slit will be mentioned several times; a point to note at present is that it allows a tapered wedge of polyethylene to be inserted in the mass slit, which largely removes the spread of momentum in the beam. This large dispersion would cause a severe loss of off-momentum particles in the second stage of the beam if a horizontally focusing field lens were not introduced at the first horizontal focus.

With the proper adjustment of this quadrupole, the transmission of the system as a function of momentum is nearly uniform over the momentum band accepted. (Figure 3 is drawn for the beam with the wedge in place. Without the wedge, the correct strength for the field lens is somewhat higher).

The following paragraphs give a brief description of the elements forming the beam, and the position along the beam Z, measured in cm from the target. Figure 4 shows the layout in the North Hall (inside the ring) of the P.S.

Description of Beam Elements.

1) Z = 0. Target: 2 (high) x 4(wide) x 38 mm long beryllium target, aligned with the secondary beam, i.e. at 15° to the proton beam, towards the inside of the ring. The efficiency for a fast (~ 1 ms) burst with this target, using R.F. steering is about one-half, as compared with a slow burst.

2) $Z = 60$ cm. Mylar windows isolating the P.S. and separator vacua, 130 microns thick. They are placed only 60 cm from the target, as compared with the distance to the entrance principal plane of 500 cm, so that they produce a negligible degradation of the image.

3) $Z = 103$ cm. A special 0.5 m magnet which bends 13.9° away from the machine, thereby causing the beam to avoid the fringing field of the next P.S. magnet and allowing the following elements to be brought considerably closer than would otherwise be possible. This magnet, which was designed by G. Petrucci, has a C-shaped yoke and "window-frame" coils, with a one cm iron stray field shield on the open side, so that it can be brought within 12 cm of the central orbit of the P.S.

4) $Z = 197$ cm. A collimator limiting the vertical aperture of the beam, brass, 0.5 m long, opening adjustable from outside the vacuum. This, and all the following slits and collimators are tapered to fit the profile of the beam, at the nominal aperture.

5) $Z = 265$ cm. Horizontally limiting collimator, similar to the vertical one.

6) $Z = 336$ cm. Horizontally focusing quadrupole, 20 cm diameter, 22 cm long.³

7) $Z = 476$ cm. One meter magnet with 11 cm gap, bending 41° .

This magnet provides sufficient vertical focusing so that the beam is slightly convergent passing through the separator, a condition which helps avoid the scattering of unwanted particles on the separator plates.

The shimming of this magnet, which will be discussed in the next section, has resulted in a small horizontal defocusing, which is overcome by increasing the gradient of the preceding quadrupole by about 10 o/o over that calculated in the usual manner.

8) $Z = 791$ cm. The first of two electrostatic separators with magnetic field perpendicular to the electric field, a unit with plates 3 m in length and a 10 cm gap, manufactured by S.C.F. of Paris. It has generally been operated with a potential 460 KV between the plates, supplied by two 600 KV. Sames units of 1 o/o regulation.

9) $Z = 1020$ cm. A 20 cm thick brass collimator immediately after the separator removes particles which are outside of the normal beam envelope either because they are not in the accepted momentum band, or because they have been scattered. The purpose of this and the next collimator is to ensure that off momentum particles will be stopped on surfaces which are roughly perpendicular to the beam, adequately thick, and not viewed by the mass slit.

- 10) $Z = 1073$ cm. Vertically focusing quadrupole, 20 D x 22 cm.
- 11) $Z = 1190$. The vacuum pipe carrying the beam (normally 20 cm OD, 19 cm ID) widens to 24 cm at this point to accomodate a 20 cm thick brass collimator at the end, which allows the off momentum particles to be stopped in a manner satisfying the conditions stated under element number 9.
- 12) $Z = 1328$ cm. The mass slit at this point fills the aperture of a 20 D x 22 cm quadrupole which acts as a horizontally focusing field lens. The mass slit, of a peculiar form which will be explained later, is brass 21 cm thick, with a minimum vertical aperture of 4 mm and a horizontal aperture of 20 cm. (This slit will be replaced by one with tungsten inserts now under construction). The mass slit is in air. There are two-mylar windows on the beam pipes a few cm from each end of the mass slit. This permits two counters on remote positioning stands to be introduced here, one before the slit and one inserted into the second half of the slit.
- 13) $Z = 1583$. One meter magnet with 11 cm gap bending 41° , with a sextupole term from shimming.
- 14) $Z = 1865$ cm. Second separator, with plates 3 m long and 6 cm (5,5 cm clear aperture) gap, built by the Padua group. It has been operated at 240 KV. The electric field is in the opposite direction to that of the first separator.
- 15) $Z = 2040$ cm. Just after the separator, there is a collimator similar to element 9.
- 16) $Z = 2070$ cm. Vertically focusing quadrupole, 20 D x 22 cm.
- 17) $Z = 2175$ cm. Horizontally focusing quadrupole, 20 D x 100 cm. long. This lens produces a horizontal focus behind the second mass slit, at a point which is convenient for the bubble chamber being used.
- 18) $Z = 2290$ cm. Second mass slit, brass 30 cm thick, minimum opening 6 mm. A movable counter is placed in front of this slit, and a final counter just before the bubble chamber. A vertical bending magnet is needed before the bubble chamber. For the Ecole Polytechnique heavy liquid chamber, this was a special 1.2 m magnet, and the overall distance from the target to the entrance of the chamber was 25 m.

III Aberrations and Corrections

There are four sources of aberration which must be discussed in a separated beamnon-linear aberrations in the bending magnets; chromatic

aberrations in the focusing elements; non-linear aberrations in the quadrupoles; and imperfections in the separator fields. For a beam with elements of typical quality, and fairly large bending angles, the aberrations due to the bending magnets are by far the largest. We have corrected the bending magnet aberrations in such a manner that the chromatic aberration can also be much reduced. The procedures used for this purpose will be described, then estimates for the other aberrations will be given to show that they are not serious.

Bending Magnet Correction

The properties of the bending magnets were measured by the floating wire method, as shown in Figure 5. The motions X_1 , X_2 , X_3 , X_4 , and corresponding motions in the vertical direction, were obtained by means of heavy milling-machine-like instruments graduated in 0.01 mm units with a 50 cm travel. X_1 held a wire support, X_4 a large pulley, and X_2 and X_3 each held horizontal and vertical telescopes for measuring the position of the wire. The bending angle of 41° was set up with a theodolite on top of the magnet. The wire current was determined by the equation for the analogue

$$i = 2.94 \left(\frac{T \text{ Gm}}{P \text{ MeV/c}} \right) \text{ amp}$$

with a tension, T , of 50.0 gm.

The quantities to be measured are the changes in bending angle and vertical focal length as the trajectory is moved away from the beam axis, consequently systematic effects such as the few millimeters of wire sag are not important.

The procedure was to set the wire on the central beam axis, adjusting the bending magnet current to make the wire come into the proper position in the telescopes; then $X_1 = X_4$, and $Y_3 = Y_4$ were displaced by the amounts necessary to reach the point in the magnet aperture to be measured. If the magnet were perfect, the displacements of X_2 and X_3 , and of Y_1 and Y_2 would be the same as of X_1 and Y_3 ; from the actual displacements required to bring the wire to the center of the telescopes, the changes in bending angle and focusing can easily be calculated. The trajectories actually measured, parallel rays entering the magnet, with a resulting vertical focus on one side, resemble nearly enough those for which the magnets are used in the beam.

The results for the vertical focal length of a one meter magnet in the standard configuration as a function of X are shown by curve 1 on Figure 6. It will be seen that the changes in focal length are of the order of 60 o/o. We wished to reduce the contribution of this aberration to the image size to the order of one millimeter or less, which means that the focal length should be constant to an accuracy of 1 o/o. The bending angle as a function of X is shown in Figure 7. A relation between the changes in focusing and bending can be found from the theory of bending magnets with gradients,⁴ and indeed these effects are consistent in the present case. It may also be shown that for the condition imposed on for the focal length, the field must be controlled (i.e., be constant or linear in X) to a few parts in 10^4 .

The correction was made by shimming the poles with 0.1 mm iron plates, retained by brass cover pieces, and by the use of 1 mm iron plates bolted to the ends of the poles.

The focal length for a corrected magnet is shown on Figure 6, Curve 3. It is satisfactory over a beam width of about 17 cm, an aperture greater than the size of the beam in the magnets.

Figure 6, Curve 4, shows the focal length of the second one meter bending magnet in the beam. The ideal focal length for this magnet is a certain linear function of X , that is to say, this magnet incorporates a sextupole term, the function of which is explained below. The variation of bending angle for this magnet is shown on Figure 8. A comparison is made with a straight line since the variation about this line gives the error contributed by the magnet to the momentum resolution ($< 10^{-3}$) and the slope of the line shows a small horizontal defocusing.

The magnets were shimmed for a beam momentum of 800 MeV/c, requiring a current of 516 Amperes. The magnets are somewhat saturated. It is interesting to observe the change in focal length when the current is changed. This effect is shown in Figure 9, for 700 MeV/c, and the resulting aberrations would be large enough to affect seriously the separation at that momentum.

The correction for the chromatic aberrations is of a different nature for the first and second vertical foci. At the first focus there is a large momentum dispersion and a good momentum resolution ($\sim 1/3$ o/o) at any given point along the horizontal image. One may ask, therefore, for the locus of the points of vertical focusing for different momenta.

Momenta less than the central value by 1 o/o will focus nearer to the target by ~ 11 cm and will have a transverse displacement of 10.3 cm due to the dispersion, thus this locus lies at $\sim 45^\circ$ to the beam axis. This effect is comparable to the dimensions of the tapered mass slit, so it is practical to make the mass slit in such a way that it lies along that line. When such a slit is studied for a typical beam, it is usually found that the angle is much larger than 45° and the scheme is impractical. The large dispersion and short focal length make it possible in the present case.

Now consider the second stage. Since the wedge at the first mass slit removes most of the momentum there is no real chromatic aberration in the second stage, but the second bending magnet, which is intended to make the beam parallel, sees a source, the cocked mass slit, of a peculiar sort. Different points on the source are at different distances from the principal plane of the magnet, which would lead to an aberration just like a chromatic aberration. It can be corrected by the introduction of a sextupole term. The fact that the bending magnet is some distance from the nominal horizontal focus is not serious: the horizontal magnification is sufficiently large that the rays for one momentum have not diverged very much in reaching the magnet, so the correspondence between points on the slit and on the magnet is good.

The method of producing the correction is shown on Figure 5, where the X_1 motion, the wire support, for bending magnet II, is shown turned to an angle of 45° to the beam. The magnet shimming was such that the rays from this source were rendered parallel, which produces just the desired effect. From Figure 6, one can see that the difference in shimming between the two bending magnets is small compared to the total amount needed.

The further aberrations expected, due to the non-linearities of the quadrupoles were calculated using the results of previous measurements.^{3,5} They give a contribution to the image width of less than one mm. The electric and magnetic fields of the separators, integrated over the length of the separator, varies by about one per cent, over the aperture used. The temporal variation of the separator high voltage supply is of the same order. These quantities must be compared with the $(\frac{1}{\beta_\pi} - \frac{1}{\beta_k}) = 0.16$.

Beam Performance

Most of the experience with the beam has been with K^+ , though the other possible elementary particles have been investigated briefly. Some of the information obtained is given in Table III. The gap in the second separator was reduced to 6 cm, giving 5.5 cm of clear aperture, to ensure that the electric field would be high enough for good separation.

This was possible since the K^+ intensity is more than adequate for bubble chamber use, with normal machine intensity and sharing half the beam with another target. The vertical collimator was adjusted to limit the beam to this aperture. (The figures in Table III are for the beam with this reduced aperture of 0.45 milliradians). To achieve the correct intensity, the solid angle was further reduced with the horizontal collimator.

The image at the second mass slit was measured with a 2 mm high counter; the limit on the image size given was obtained assuming a quadrature folding law. It is seen that the image size obtained is consistent with that calculated without chromatic aberration. The positions of the vertical images for particles of opposite sign indicates that the vertical alignment of the elements has been performed with an accuracy of better than one mm.

Since it was not convenient to reduce the machine intensity ($\sim 5 \times 10^{10}$ p) during there runs, counting loss limited to the accuracy of the direct measurements of the pion flux. For this reason, the pion flux from an integration of the beam profile with a small (20 mm^2) counter is given in Table III.

The tuning of the separators was done in the usual way for a two stage beam: the first separator voltage and magnet current were set at a fixed value, and the current in the second separator magnet varied. The second stage is thereby used to perform a mass analysis of the output of the first stage. By varying the current in the first separator, an optimum value is found. This process was facilitated by the use of time of flight discrimination using the flight path from the second mass slit to the bubble chamber, i.e. counters number 2, 3 and 4.

Mass curves taken with delays set for π (or μ) and for K mesons are shown in Figure 10 (a). These curves, taken under good beam operating conditions, show a very small $\pi + \mu$ contamination in the K^+ peak. The number of $(\pi + \mu) / K$ arriving at the second mass slit is given by the ratio of the two peaks, but this result is somewhat optimistic since the requirement is

made that the particle pass through C2, which does not cover all of the beam. Figure 10 (b) shows a mass curve taken with the counter before the second mass slit; and indeed a somewhat higher ratio of $(\pi + \mu) / K$ passing through the first slit is found, but a well separated peak is still evident. The $(\pi + \mu)$ contamination in the K peak is difficult to obtain with the single counter, because of background. From the counter measurements, and from delta rays in the bubble chamber, a contamination of 5 - 10 o/o is found in the K^+ peak. The less abundant antiprotons are also well separated, with a contamination of ~ 10 o/o.

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Table I

I (a) Target Fluxes (See Table III for the results with this beam).

Particle	Momentum GeV/c	Angle	Proton Energy GeV	Flux particles per proton GeV/c steradian	Reference
K^-	0.8	15°	18.	$1.3^{+0.3} \times 10^{-3}$	1
K^-	1.3	15°	18.	2.3×10^{-3}	1
K^-	1.25	20°	29.5	$1.4^{+0.4} \times 10^{-3}$	2
K^+	0.8	15°	18.	$2.7^{+0.5} \times "$	1
π^+	0.8	15°	18.	1.3×10^{-1}	1

I (b) Factors to give the number of K^- stopping.

1. Decay loss; for $p = 800$ MeV/c:

	K	π
18m	20.5	1.6
25m	66.	1.9

2. After degrading in copper, so that the K^- come to rest in liquid hydrogen, the range spread due to a momentum spread in the 800 MeV/c beam is 1.43 gm / 1 o/o $\Delta p/p$ - 23 cm / 1 o/o $\Delta p/p$ in bubble chamber hydrogen. The effect of straggling gives a width ($\pm$ one standard deviation) of 29 cm of liquid hydrogen.

3. The estimated loss in degrading 800 MeV/c K^- in copper to come to rest in 35 cm of hydrogen is 8.3.

Table II

Beam Parameters

Parameter	1st stage	2nd stage
Length ⁽¹⁾	13.3 m	9.6 m (22.9m overall)
Solid Angle ⁽²⁾	0.6×10^{-3} str.	$(0.45 \times 10^{-3}$ str.)
Separator Gap ⁽²⁾	10 cm	(6 cm)
Separator Plate Length	3m	3 m
Separator Voltage	460 KV	240 KV
Horizontal Magnification	4.9	0.19 (0.9 overall)
Vertical Magnification	0.54	1.33 (0.72 overall)
K - π separation	8 mm	8 mm
Momentum dispersion ⁽³⁾	10 cm/1 o/o $\frac{\Delta p}{p}$	0.4 cm/ 1 o/o $\frac{\Delta p}{p}$

Notes:

1. The overall length given is to the 2nd mass slit.
The distance to the bubble chamber is ~ 25 m.
2. The overall solid angle of the beam is 0.6×10^{-3} str.
when an 8 cm gap is used in the 2nd separator.
The performance figures of the beam are given for a 6 cm gap (5.5 cm clear aperture) which gives a solid angle of 0.45×10^{-3} str.
3. The momentum band accepted was $\Delta p = 15$ MeV/c.

Table III

Beam Performance

III (a) Particle Fluxes (1).

Particle	Flux at 23 m from target, per 10"p	Flux corrected for decay per 10"p	Absolute Flux ⁽²⁾ per 10"p-steradian - GeV/c
π^+ (π^- Flux = π^+ Flux)(3)	0.36×10^5	0.6×10^5	-
π^+ (4)	$(0.5^{+0.1}) \times 10^5$	$(0.85^{+.15}) \times 10^5$	0.15 ± 0.02
K^+	57 ± 11	2700 ± 500	$(5.3^{+1.}) \times 10^{-3}$
K^-	21 ± 4	1000 ± 200	$(1.9^{+.4}) \times 10^{-3}$
$\bar{p}$	5 ± 2	-	$(1.2^{+0.4}) \times 10^{-5}$
p	0.25×10^5	-	$(6.8^{+2.}) \times 10^{-2}$

Notes:

(1) Particle fluxes for a momentum of 800 MeV/c and an angle of 15° , from 18 GeV protons on Be. The solid angle of the beam was $\Omega = 0.45 \times 10^{-3}$ steradiane and the momentum band $\Delta p = 15$ MeV/c.

(2) Corrected for loss due to multiple scattering in the counter at the first mass slit.

(3) Measured with a counter covering the whole beam, not corrected for counting loss.

(4) Measured by integrating the beam image with a small counter.

III (b) Vertical Image Sizes

	Vertical image, full width, 1/2 height	
	1st Stage	2nd Stage
Calculated image of target	1.1 mm	1.4 mm
Calculated image size (including chromatic aberration)	-	3.3 mm
Measured image size	< 3 mm	< 2.3 mm

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Figure Captions

Figure 1 - An estimate of the number of K^- stopping in liquid hydrogen as a function of the beam momentum, for two forms of the K^- momentum spectrum of the target.

Figure 2 - A schematic drawing of the extreme rays in the vertical planes, for the central momentum.

Figure 3 - A schematic drawing showing the envelope of the beam in the horizontal plane, for ± 0.9 o/o $\frac{\Delta p}{p}$.

Figure 4 - The layout of the beam in the North Hall of the CERN P.S.

Figure 5 - A schematic drawing of the equipment used for the floating wire measurements.

Figure 6 - Measurements of the vertical focal length of a one meter bending magnet.

Figure 7 - Change of the bending angle of a standard bending magnet, as a function of the transverse position of the trajectory.

Figure 8 - The change of bending angle in a shimmed magnet.

Figure 9 - The change in focal length as a function of transverse position of a one meter bending magnet. This magnet, which had been shimmed for 800 MeV/c particles, was set for 700 MeV/c particles.

Figure 10 - Curves showing the mass analysis by the second stage of separation, of the particles transmitted by the first stage.

Figure 1 . Number of Stopping

K^- for Different

Transport Momenta

— K^- Flux $\propto p$

- - - K^- Flux $\propto p^2$

18m Beam

25m Beam

(X2)

FIGURE 3 - HORIZONTAL PROFILE FOR OFF-MOMENTUM RAYS
(WITH WEDGE ABSORBER)

FIGURE 5 — WIRE MEASUREMENT LAY OUT

Figure . 6.

BENDING MAGNET VERTICAL
FOCAL DISTANCE, AS A
FUNCTION OF TRANSVERSE
POSITION.

- ① — Std. B.M.- 7x30 mm shim
- ② — TAPERED POLE B.M.,
7x30mm SHIMS, 30x130 mm
END PLATES
- ③ — ○ — "B.M. I" See text.
- ④ — - - - + - - - "B.M. II"

Figure 7

BENDING ANGLE CHANGE

STANDARD MAGNET $\theta \approx 41^\circ$, $p = 800 \text{ mev}/c$

GAP = 11 cm MEASURED IN PLANE 15 mm

FROM POLE.

Figure 8

BENDING ANGLE CHANGE

BM II $\theta = 41^\circ$ $p = 800 \text{ MEV}/c$

11 cm gap Measured in plane 15 mm

from pole

Figure 9

CHANGE OF FOCAL DISTANCE WITH
MOMENTUM. WITH B. M. II, SHIMMED
FOR 800 mev/c AND BENDING ANGLE = 41°
 $P = 700 \text{ mev/c}$

Figure 10 Mass Analysis of Beam Transmitted by
First Stage of Separation