RF SEPARATORS AND SEPARATED BEAMS AT SLAC*

SLAC-PUB-1552
March 1975

T. H. Fieguth and R. A. Gearhart

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Introduction

It has been shown that with momenta above ~5 GeV/c, the only effective means of separation by particle mass in secondary beams is using RF deflectors.[1,2] Particle separation at proton synchrotrons requires the use of two RF deflectors. The beam structure at SLAC permits the use of a single deflector.

General Description

Panofsky[3] originally suggested the use of two RF deflectors for secondary beams at proton synchrotrons. The idea was further advanced by Schnell[4] and is shown schematically in Fig. 1 as designed and built at CERN in 1966. An RF separator (RFS) is placed early in a momentum analyzed secondary beam to modulate the beam and a second RFS is inserted at a drift length L. The phase angle of a particle of mass m and momentum p (relative to a particle of β=1) at the second RFS is given by

$$\phi = \frac{2\pi L}{\lambda}\left[\sqrt{\frac{m^2}{p^2}+1}-1\right] \text{ where } \lambda = \text{RFS wavelength} \qquad (1)$$

$$\simeq \frac{\pi L}{\lambda}\left(\frac{m^2}{p^2}\right) \text{ for } p \gg m \qquad (2)$$

Given the maximum transverse momentum $p_\perp$ imparted to the beam, the deflection angle θ is

$$\theta = \frac{p_\perp}{p}\sin\phi \qquad (3)$$

For two particles of different mass

$$\Delta\phi = \frac{\pi L}{\lambda}\left[\frac{m_1^2 - m_2^2}{p^2}\right] \qquad (4)$$

Between the separators is a lens system imaging the first onto the second with unit magnification. The first RFS deflects both wanted and unwanted particles indiscriminately. The phase of the second is maintained at the same relative phase as the first for the unwanted particles. Thus the net deflection for unwanted particles is always near zero. A beam stopper is placed along the beam axis following the second RFS to intercept the unwanted particles. For wanted particles the phase at the second RFS relative to that at the first is $\Delta\phi$, given in (4). The net deflection can range from zero to θ_{max}. Depending upon the geometry of the beam stopper, the transmission efficiency for wanted particles is limited to ~2/3. Further, the RF deflectors are pulsed devices with pulse lengths of the order of a few μs, thereby limiting the duty factor, and the general usefulness of the technique is limited to bubble chamber beams. Similar beams were constructed at BNL[5] and ANL.[6] The frequency for practical RF deflectors has been optimally chosen to be S-band (2856 MHz);[1,2] the determining factors in the choice are power densities, aperture size and commercial availability of acceptable peripheral components, notably klystrons.

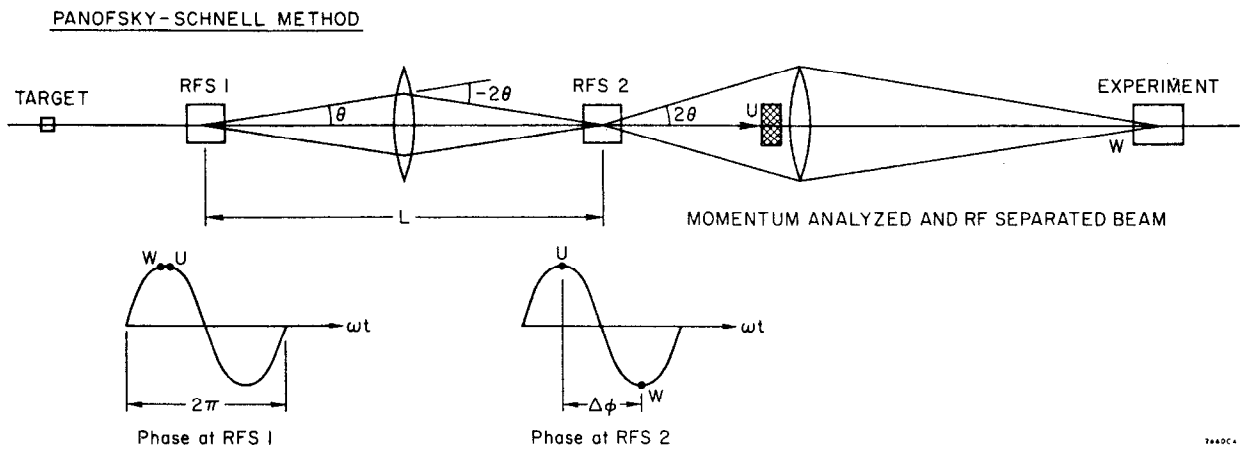

FIG. 1--Schematic of Panofsky/Schnell separated beam.

At SLAC, the primary beam has RF structure at a frequency of 2856 MHz with beam limited to ~5° of phase.[7] Thus the beam occurs in 5 ps bunches separated by 350 ps within a pulse length of 1.6 μs. As the inherent RF structure is retained in secondary beams†, a single RFS located after a drift length L will enable particle separation to be accomplished. As shown in Fig. 2, L used in Eqs. (1) - (4) above is now the distance between the target and the RFS.

Phillips[8] built and tested rudimentary cavity deflectors at Stanford in 1958/1960. A circularly polarized mode was used and deflections of 0.8 MeV/c were measured. Later, in 1963, Altenmueller et al.[2] designed, built and tested two prototype cavities at the Stanford Mark IV accelerator; the results led to the design of the SLAC RF separators (see Table I and Fig. 3). Three important features should be pointed out: 1) the phase shift per cavity is $2\pi/3$; 2) the field is linearly polarized by suppression holes; and 3) the deflection is uniform over the circular aperture.

RF Separated Beams

Beam line 6 (BL 6) was the first RF separated beam to be built at SLAC (1966), designed to be a 12 GeV/c K^+ source for the 82" hydrogen bubble chamber. A bandpass at this momentum for kaons requires a drift length of 70 m where the K's are 180° out of phase with both π's and protons

*Work supported by the U.S. Energy Research and Development Administration.

†There are effects which tend to disrupt the isochronism of the beam: 1) nonzero production angle (negligibly small for typical angles of ~3°); 2) path length differences dependent upon beam optics (~0.4 cm compared to the RF wavelength of 10.5 cm); 3) momentum spread, particularly of protons.

(Presented at the 1975 Particle Accelerator Conference, Washington, D.C., March 12-14, 1975)

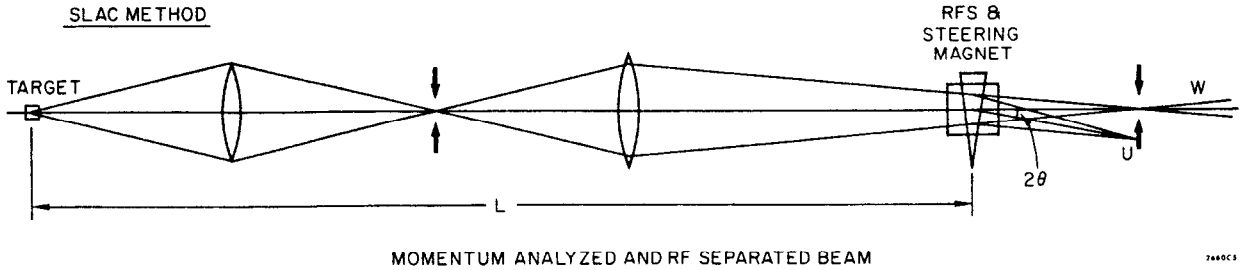

FIG. 2--Schematic of SLAC separated beam.

TABLE 1

PARAMETERS OF THE SLAC RF SEPARATOR

	Mod I	Mod II
Frequency	2856 MHz	2856 MHz
Mode Family	HEM_{11}	HEM_{11}
Phase Shift/Cavity	$2\pi/3$	$2\pi/3$
Total Cavities	71	104
Periodic Length (d)	3.5 cm	3.5 cm
Cavity ID (2b)	11.634 cm	11.634 cm
Iris Diameter (2a)	4.4882 cm	4.4882 cm
Outside Diameter	13.759 cm	13.759 cm
Separator Length	3.64 m	2.48 m
Quality Factor	12,100	12,100
Group Velocity	-0.0189	-0.0189
Attenuation/Meter	0.131 np/m	0.131 np/m
Transverse Momentum	25 MeV/c	25 MeV/c
Typical Operating Power	25 MW	30 MW
RF Pulse Width	2.5 μs	2.5 μs
Pulse Rate	60 pps	180 pps
Maximum Pulse Rate	180 pps	180 pps
Phase Adjustment	0 - 360°	0 - 360°
Operating Temperature	45°C	30°C
Quantity Available	1	3

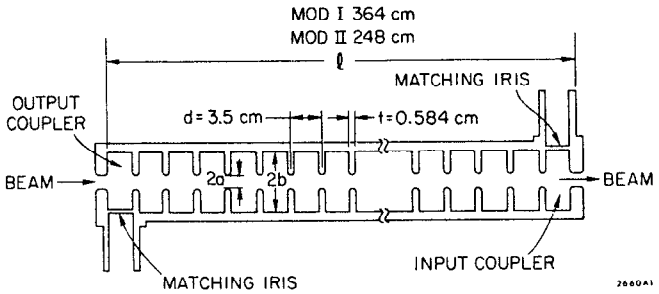

FIG. 3--Diagram of SLAC RFS (see Table I).

(see Table II). With $p_\perp = 25$ MeV/c the angular separation between the beam components is 4×10^{-3} radians at 12 GeV/c. A drift length of 6.4 m from the effective center of the RFS to the second focus collimator results in a spacial separation between the wanted and unwanted components of the beam of 2.5 cm at the upstream end of the collimator, a separation slightly larger than the collimator aperture.

Table II. Beam Line Parameters and Bandpass Momenta

Beam Line	6	14	21*		23
RF Separators	1	1	2		1
L (meters)	70	67	36	79	75
Bandpasses (GeV/c)					
$K^\pm$	6.9	6.8	4.9	6.4	7.2
	12	11.6	8.5	10.9	12.3
$p^\pm$	9.1	8.9	6.5	7.3	9.4
Total Length (meters)	137	96	149		130
Acceptance (μster-%)	75	47	66		15 (75 max)
Production Angle	1.6°	1.1°	1.0°		1.5°
Experimental Facility	Tests 82" HBC	SHF (1 m HBC)	LASS		Streamer Chamber

*Bandpasses shown for beam line 21 are for a single RFS. In general, both are used (see Fig. 5).

It can be seen from Fig. 4 that the π^+/K^+ production ratio is large; therefore for a K^+ beam, the rejection efficiency for π's must be quite good. Rejection has been measured to be $\sim 2\times10^3$ at 12 GeV/c. The RFS can be used to clean up a virtual continuum of pion momenta; this is typically done.

As other beams were designed at SLAC, a need for additional RF separators was generated. It was decided to build three additional units with the only substantial changes being a reduction in length to 2.5 meters and a more compact strongback design. The reduction in length was made without sacrificing transverse deflection due to increased power capabilities from the SLAC klystrons. Of these three new separators two were installed in BL 21 to the large angle solenoid spectrometer (LASS) and one in BL 23 to the 2-meter streamer chamber. These two beams have essentially the same acceptance and optical properties.*

The present configuration of BL 23 can be used to illustrate the optimization of primary beam energy, current and repetition rate for given secondary beam requirements. The present streamer chamber experiment requires an acceptance of 15 μ steradian-%, a factor of 5 smaller than nominal. Figure 4a shows the relation of primary beam energy to current required to deliver 10 π^-/pulse to the streamer chamber for different secondary momenta. It can be seen that a momentum of 15 GeV/c is attainable; however, a further consideration is beam purity. 14 GeV/c is chosen so that the RFS can be used to remove the 1.5% K^- contamination.

Figure 4b gives the calculated and measured fluxes for BL 21. It can also be used for BL 23; however, the bandpass momenta and overall length are different. Calculated fluxes as shown in Fig. 4 are calculated from

$$N = YA(\delta)\exp\left(-\frac{t}{\beta\gamma\tau}\right)\exp\left(-\frac{D}{p}\right) \text{ (particles/mA-pulse)}$$

$$Y = Y(E, p, \theta, X) \qquad \text{(Ref. 9)}$$

for production angle θ, primary e^- energy E and target factor X. In general, Y is functionally different for each particle type. The acceptance $A(\delta) = \Omega(\delta)\cdot\delta$ where $\delta = \Delta p/p$ (full width) and where $\Omega(\delta)$ is the solid angle function as determined from Monte Carlo calculations.[11, 12] Typical shapes of $\Omega(\delta)$ and $A(\delta)$ are shown in Fig. 5. An empirically determined factor D corrects for scatterers (vacuum windows, air paths, detectors and electron filters) and for accumulated aberrations.[13] The fluxes in Fig. 4b were measured by SLAC's Group B[10, 14] and are normalized to 66 μ ster-%. It can be seen that the agreement between calculated and measured values is quite good.

Beam line 14 (BL 14) is being modified to provide a separated beam to SLAC's 1 meter hybrid bubble chamber facility (SHF). Figure 4c shows the expected particle flux at the bubble chamber. Properties of the beam line are similar to those of BL 6 with the exceptions of overall length and that the beam has no achromatic focus. At the point of separation the momentum dispersion is 1.5 cm/% and limits δ to 3%.

Computer generated graphics for deflections of unwanted particles at the defining collimator is illustrated

*The rather unique optics is described elsewhere.[10]

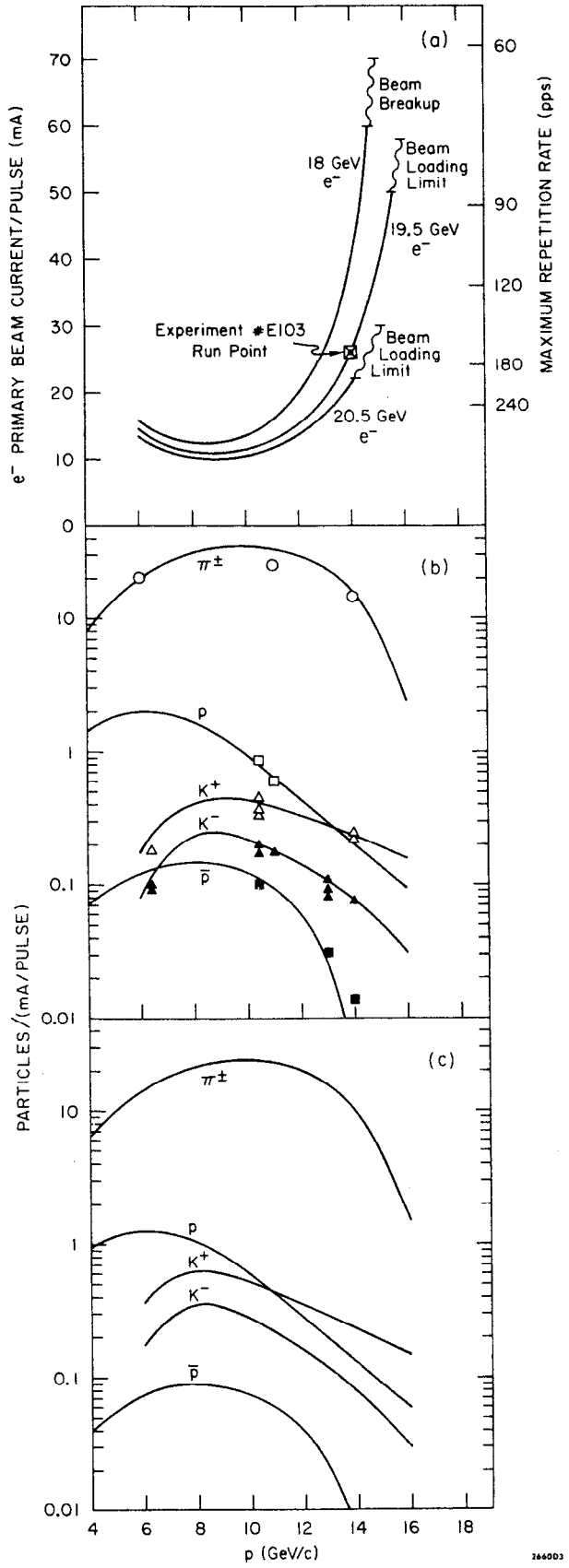

FIG. 4--a) Required primary beam energy and current for 10 π^-/pulse in BL 23 at the streamer chamber. Rate limits are for 19.5 GeV.
b) Measured and calculated fluxes in BL 21 at LASS.
c) Calculated fluxes in beam line 14 at SHF.

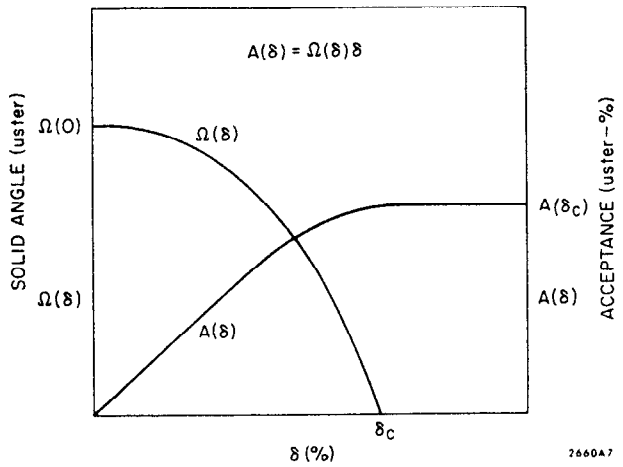

FIG. 5--Illustration of solid angle Ω and acceptance A as a function of $\delta = \Delta p/p$.

in Fig. 6. The phase of the wanted K's is set for maximum deflection; curves for maximum separation have also been generated. Figure 5c shows the result of summing the individual deflections.

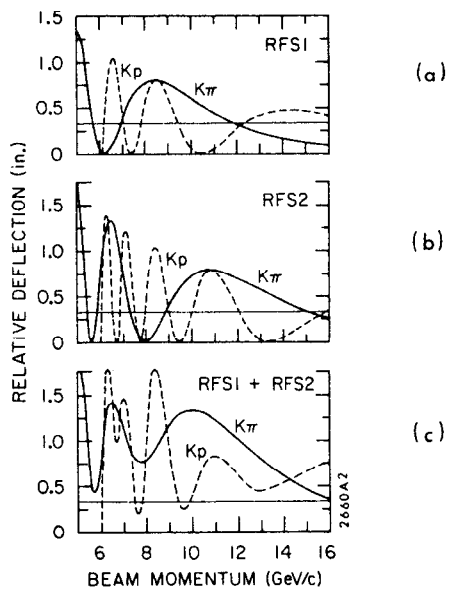

FIG. 6--Deflections of π's and protons from K's at the defining collimator in BL 21. a) RFS1 alone, b) RFS2 alone, c) RFS1 and RFS3 combined.

Tuning

The addition of a small dipole magnet centered on the RFS has proven to facilitate the beam tuning of both separated and unseparated beams. When used with an RFS, the magnet is normally set to a level compensating the RF deflection, thus giving zero net deflection to the wanted particles and 2θ deflection to the unwanted particles. The magnetic field has no deleterious effect on the operation of the separator.

As an example, a separated K beam is desired at 6.85 GeV/c, where in the unseparated beam $\pi/K \simeq 60$ and P/K is negligible. A standard technique is to first optimize the beam with the RFS off. Once optimized, the RFS is turned on, and the phase and the magnet current set such that the π's are transmitted efficiently at peak deflection. The primary beam current is raised to provide the desired K flux and the phase is rotated to transmit K's. The magnet is used to establish the direction of the phase rotation. By sweeping the magnet current, rejection can be measured as

shown in Fig. 7. Note that the π background is ~3% even with a rejection factor of $\sim 2\times 10^3$.

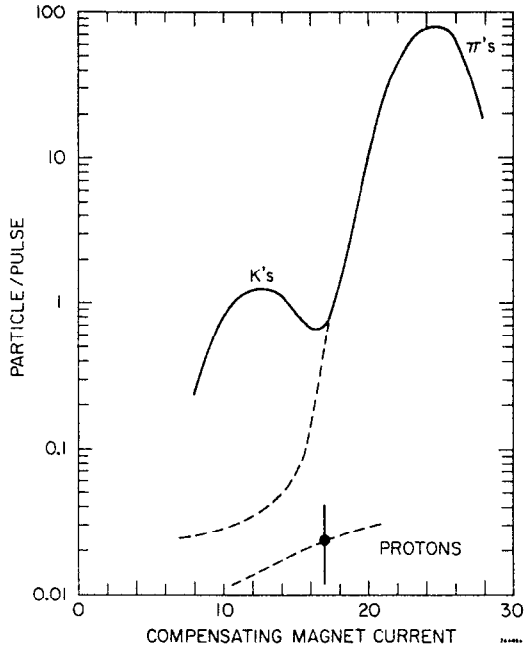

FIG. 7--π-K rejection curve at 6.85 GeV/c in BL 6.

A recently developed technique for tuning has been applied in BL 21. Two scintillators of 6 mm width and 3 cm separation are remotely positioned in the unwanted π beam at a location downstream of the RFS. The position and the integrated photomultiplier signals are use to measure and monitor the π deflection.

RF Drive, Timing and Phasing

A drive line operating at 476 MHz runs the length of the two-mile accelerator and into the research yard. At each sector this signal is locally multiplied to 2856 MHz and amplified in sub-boosters providing drive power to the klystrons. In the research yard there is an additional sub-booster used for drive power to the RFS klystrons. The separators are not closely grouped so that the drive power must be distributed over distances of ~75 meters. Care must be taken in balancing the power output available to insure sufficient drive for all five RFS klystrons.

Operating the RF separators at a constant repetition rate is important in maintaining phase and amplitude stability. The separators are each operated at a rate equal to or greater than the beam rate. The RFS rate is periodic at 60, 120 or 180 pps. This enables the use of so-called "reject" klystrons not capable of operation at 360 pps for use on the accelerator but serviceable at a lower rate. This is an important economic consideration.

The timing of the separator pulse with the arrival of the beam is easily accomplished by setting a delay of ~1 ms from a reference pulse preceding the beam. There is also a longer delay of ~40 μs after beam time that can be switched in such that the separator is on "standby".

Phase is varied remotely with a continuously adjustable phase drum; relative phase is displayed on a digital voltmeter. Short time phase stability is very good although there are diurnal fluctuations ~90° due to temperature changes on exposed portions of the RF distribution. Temperature sensitive feedback compensation has been added limiting diurnal fluctuations to a few degrees.[15]

Miscellaneous

SLAC is following a program of limiting electric power consumption. One effect has been to lower the temperature of the magnet cooling water from 30°C to 24°C. This temperature change results in a detuning of the RFS inducing a slippage of 40° in phase over its length.[16] For deflection angle θ and phase slip of 2α it can be shown[1] that the expected value of deflection $\langle\theta\rangle$ is given by

$$\langle\theta\rangle = \frac{\sin\alpha}{\alpha}\,\theta \quad .$$

For $2\alpha = 40°$ this results in only a 2% loss in $p_\perp$.

Vacuum in the RFS is maintained at $\sim 10^{-8}$ torr. Because of the high electric fields developed in the separator, out-gassing can cause intense bursts of x-ray radiation. Peak radiation is axial and has been measured to be 5R/h but the average levels are low. The addition of 6 mm of lead is adequate shielding in the radial direction. Axially, access is limited by beam pipes and protection devices.

Special Applications

The use of the BL 6 RFS as a timing device with 1 ps resolution was recently made.[17] The measurement was of the relative velocity of electrons and gamma rays at 15 GeV. The e's and γ's were made to drift over a length of ~1000 m and then impinged upon separate targets, each producing beams of positrons. The targets were imaged at a detector located downstream of the RFS, where changes in the spatial separation were measured with a sensitivity of 0.18 mm/° phase. No significant difference in velocities was observed to within ~2 parts in 10^7.

BL 6 has also been tuned to deliver a relatively low momentum π^+ beam at 3.8 GeV/c to the bubble chamber. At this momentum, $\pi/p \sim 10\%$ in the unseparated beam. However, owing to the low velocity of the protons ($\beta = 0.872$) the phase slippage over the length of separator is $\sim 2\pi$ radians; the result is a net zero deflection for protons. The π's are deflected an angle

$$\theta = \frac{p_\perp}{p} = 6.6\times 10^{-3} \text{ radians for } p_\perp = 25 \text{ MeV/c} \quad .$$

This angle is sufficient for excellent rejection of the protons.

References

1. B. W. Montague, Progr. Nucl. Tech. Instr. 3, 1 (1968).
2. O. A. Altenmueller, R. R. Larsen and G. A. Loew, Stanford Linear Accelerator Center, SLAC-17 (1963).
3. W.K.H. Panofsky, High-Energy Physics Laboratory, Stanford University, HEPL-82 (1956).
4. W. Schnell, CERN 61-5 (1961).
5. H. Hahn, H. J. Halama, H.W.J. Foelsche, Brookhaven National Laboratory, BNL-AADD-91 (1965).
6. J. H. Martin, Argonne National Laboratory, ANL-JHM-8 (1967).
7. O. H. Altenmueller, R. R. Larsen and G. A. Loew, Rev. Sci. Instr. 35, 438 (1964).
8. P. R. Phillips, Rev. Sci. Instr. 32, 1 (1961).
9. SLAC Users Handbook, Section C2.
10. F. C. Winkleman, Stanford Linear Accelerator Center, SLAC-160 (1973).
11. C. A. Gaw, "LLURCH", internal communication, Argonne National Laboratory (1969).
12. K. L. Brown and Ch. Islin, "Decay Turtle", CERN 74-2 (1974).
13. J. J. Murray and R. A. Gearhart, private communication (1974).
14. R. Cashmore, private communication (1973).
15. R. Wilson, private communication (1973).
16. G. A. Loew, private communication (1974).
17. Z.G.T. Guiragossián, G. B. Rothbart and M. R. Yearian (Stanford University), and R. Gearhart and J. J. Murray (Stanford Linear Accelerator Center), Phys. Rev. Letters 34, 335 (1975).