LONG DUTY CYCLE BEAM SEPARATION DEVELOPMENTS*

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(presented by H. W. Foelsche)

Abstract

The subject of beam separators with long duty cycle for electronic experiments is reviewed. Room-temperature long-pulse RF beam separators and superconducting RF separators are discussed with emphasis on recent beam design studies at Brookhaven. For room-temperature devices the high power requirements mandate a choice of very long traveling wave structures embedded in an optical focusing channel. Specific beam designs for intermediate and high energy regions have been studied and a new matching system for high solid angle has been designed. Expected particle yields for various separation techniques are compared. Maximum yields of the order of 10^6 K^+-mesons per 10^{12} interacting protons seem achievable at the AGS.

Introduction

Long pulse RF separated beams have long been considered desirable for counter-spark chamber experiments in the region of secondary particle momenta greater than 5 GeV/c. Such beams will become very attractive with the increased particle yields expected at the AGS and the CPS, after their improvement programs are completed.

Efforts to develop superconducting RF cavities have been underway at several laboratories, and new results have recently shown that cavities with sufficient field strengths for useful separated beams can be obtained.1) In the past two years separation methods based upon room temperature deflectors have also been studied. Due to the high power dissipation at room temperature one must work with low electric fields and must use long structures to achieve sufficient separation. In particular a long dielectric-loaded traveling wave structure embedded in a magnetic focusing channel2) and a sequence of low power iris-loaded copper waveguides alternating with the lenses of a focusing channel3),4) have been considered as possible alternatives to rf superconducting separators, and preliminary beam designs were outlined. In treating the interactions of the deflected particles with the magnetic focusing lenses the idea of allowing the RF phase to slip with respect to the particle motion at the betatron frequency was rediscovered. It had originally been proposed some 10 years earlier by Lapostolle.5) Further analysis6) showed that somewhat greater separation could be realized by allowing the traveling wave to be synchronous with the wanted particles, with the RF phase switched every half betatron wavelength ("phase switch technique"). Beams based upon dielectric-loaded2) and low power conventional deflectors3) for the momentum ranges 5-15 GeV/c and 2-8 GeV/c respectively and upon two superconducting S-band deflectors in the 8-20 GeV/c range have been designed.7) In this paper we reconsider separation in the 3-15 GeV/c range with conventional and superconducting RF deflectors. Maximum yields of the order of 10^6 K^+- mesons per pulse seem achievable at the relatively modest separator field levels achieved in the laboratory so far.

RF Deflectors

For room temperature RF separation it seem best to adopt (as suggested by H. Hahn2)) the familiar iris-loaded copper structure. Convenient power sources are available at 2.45 GHz and this frequency is not far from optimum for AGS energies. A 3m long deflector unit, operated in the ($4\pi/5$)mode, with a beam hole diameter of 4.7cm provides a transverse impulse of 0.9 MeV/c at an input power of 35 kW. A beam design by Sandweiss et al.3) would employ 4 such deflectors in a focusing channel and cover the kaon-momentum region from 3-6 GeV/c. To build a beam with twice the maximum energy would require four times the separator length i.e. 16 such room temperature deflectors in a focusing channel.

Superconducting Nb cavities are holding out the promise of higher deflection fields and, therefore, larger separated beam yields. The main limitation here is either the peak electric field E, or the peak magnetic field B which can be supported in the walls of the structure. A secondary limitation is the Q of the cavity which determines the total amount of refrigeration. Although more efficient biperiodic deflector structures have been proposed we consider here a simple $\pi/2$ cavity, differing little from the presently used BNL structure, with a 4 cm beam hole operating at 2.86 GHz. For this cavity the ratio of peak magnetic field B to average deflecting field E_o (standing wave mode) is B/E_o = 155G/(MV/m), E/E_o=5.5, and the shunt impedance is given by R/Q = 760Ω8). Using a conservative estimate of possible peak magnetic fields B = 300 G yeilds E_o = 2MV/m. This is seven times the gradient which can be achieved for room-temperature long duty cycle deflectors. With a superconducting improvement factor of only 5×10^4 it requires 10W of refrigeration at 1.8°K per meter of structure. Four one-meter long superconducting deflectors in the Sandweiss beam would thus provide more than twice the deflection of the four conventional ones. For a beam with twice the maximum energy it suffices to build 3 cavities 3m long each.

Intermediate Energy Separator Channel

A basic RF separator channel one half betatron wavelength long with room temperature CW deflectors had been proposed by Sandweiss3) et al. during the 1970 BNL Summer Study. This basic channel is a symmetric array of five uniformly spaced alternating gradient lenses. Between input and output there is negative unity magnification and the off diagonal transfer matrix elements are zero in both planes. The lens spacing is 4m, the RF deflectors are inserted in the four gaps between lenses and the channel is 16m long, see Fig. 1. Room temperature deflectors would fill these four gaps entirely.

As a variation of the Sandweiss design, we consider here substituting 1m long superconducting cavities. The number of parameters available for optimizing the angular separation of particles from two

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other beam constituents is indeed large: three independent deflection amplitudes and phases and, in the room temperature separator, phase velocity as well. At the output of the separator channel the wanted and unwanted particle beams oscillate in time with different angular amplitudes W and U respectively (U being defined here as the larger of the two unwanted ones). One can achieve excellent separation over a wide momentum band, and some of the possibilities are shown in Fig. 1. These are the results for short point deflectors located in the center between the lenses. The effects of the phase slip of particles with respect to the deflecting waves in longer room-temperature structures are not shown. The separation $S \equiv W - U$ is plotted in such units that the deflector which requires the largest amount of power would contribute a unit amplitude if it were in free space without channel quadrupoles. For the conventional deflector this unit is a transverse momentum of 0.9 MeV/c, and for a 1m long superconducting cavity as described above this unit is 2 MeV/c. At momentum p, the angular separation at maximum overall deflection is then proportional to S/p. Curve A represents the "phase switch" case: the phase between the second and third cavity is switched 180° so that all deflections interfere constructively for maximum angular deflection of wanted particles; curve B gives the optimum that can be achieved with 4 deflectors if both unwanted deflections are reduced to zero; and curve (C) what can be achieved with three deflectors (leaving out one of the center ones) cancelling both contaminant amplitudes.

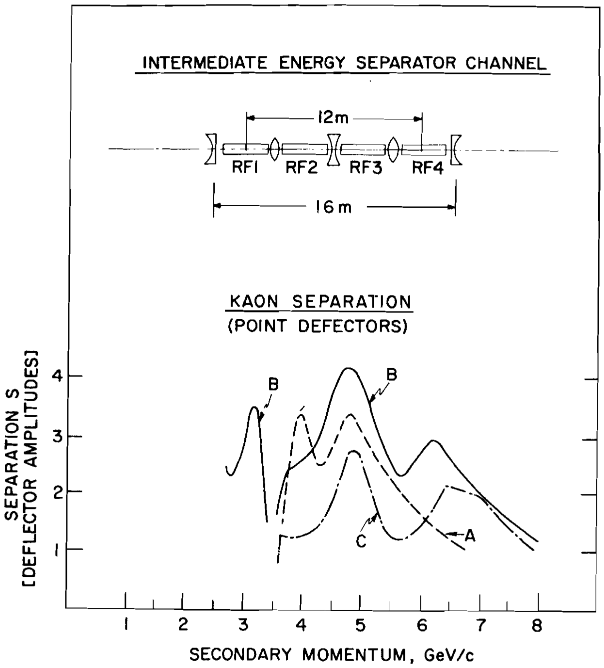

Fig. 1. Intermediate Energy Separator Channel Kaon passbands using 3 or 4 superconducting point deflectors (see text for details)

High Energy Separator

Another beam separator examined here is for a momentum range approximately twice that of the foregoing case. For room temperature deflectors, one could replicate the basic separator channel four times, filled with 16 deflectors a total separator length of 64m. This configuration can yield momentum passbands similar to Fig. 1, with the momentum scale expanded by x2, and the vertical scale x4.

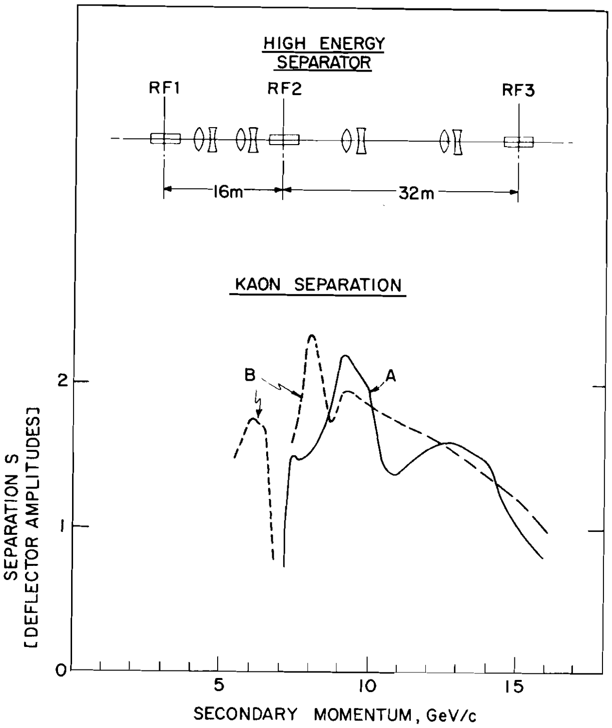

Fig. 2. High Energy Separator Kaon passband (see text)

The higher electrical fields in a superconducting separator enables one to consolidate the separator into 3 properly spaced deflectors, RF1-RF3, 3m long each, with a peak transverse impluse of 6 MeV/c contributed by each. The spacing is 48m between the outer cavities, the center cavity is 16m from the first one(see Fig. 2). Half wavelength channels of the type described above match one cavity onto the next. This arrangement provides the kaon passband of Fig. 2. The separation S for kaons, again normalized to the amplitude of the deflector with the largest power requirement, is plotted for 2 cases: Case A, the three-cavity passband of Schnell[9] with pion and proton deflections cancelled (the three deflector amplitudes are generally not the same in this case), and Case B, the result of optimizing the phasing of three equal deflector amplitudes for maximum separation of kaons (the unwanted particles are generally not cancelled in this case).

Optical Match from Target to Separator

A large solid angle matching system has been

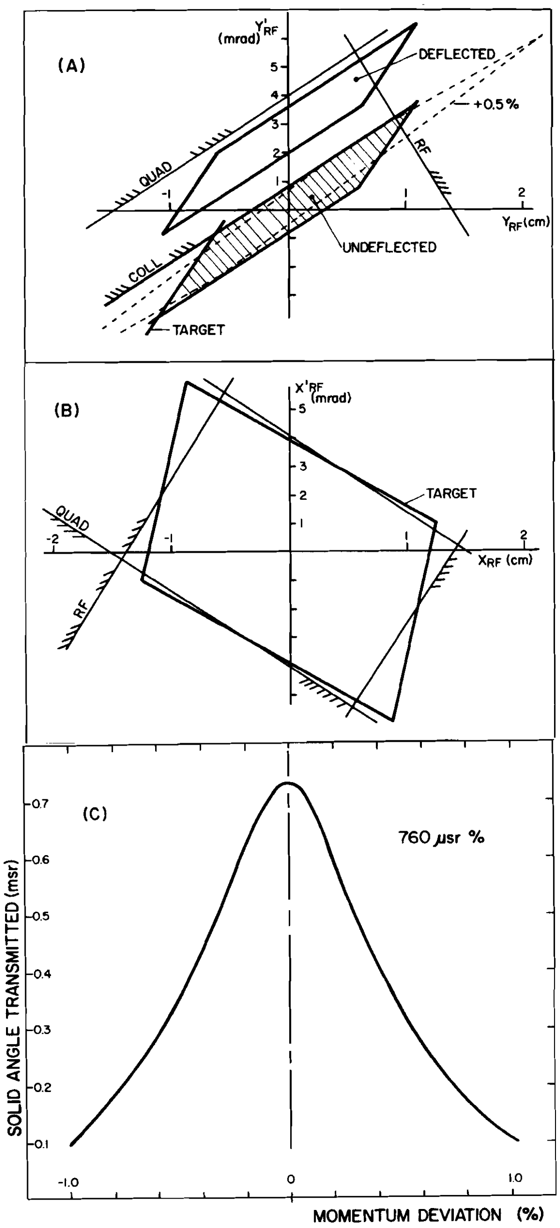

Fig. 3 (A) Vertical phase-space match and (B) horizontal phase-space match at the center of the first deflector. (C) transmitted solid angle as a function of momentum deviation.

designed, fully exploiting the phase space acceptance of the separator stage. We describe here the match for the high energy superconducting beam. With a minor modification it can also be applied to the separator channels. Following the suggestion of H.N. Brown[2)] the match is accomplished by a triplet near the target, with large magnification in both planes, and a singlet near the first deflector. Fig. 3 shows vertical and horizontal phase space matching achieved at the center of the first cavity. The target is 1.5mm high and 3mm wide. The following limiting apertures are shown: one of the downstream quadrupoles ("QUAD") imaging the first deflector onto the next with limiting aperture of 10cm diameter (7cm inscribed square assumed) and the cavity ("RF") with a deflector aperture of 4cm (2.8cm inscribed square assumed).

The vertical phase space is further limited by an angle defining collimator ("COLL") between the triplet and the singlet upstream of the first deflector. It is important to realize that this angular definition is practically free of chromatic aberration because this collimator is viewed only through the singlet lens upstream of the deflector. Wanted particles are separated in angle only as shown by the "deflected" phase space in Fig. 3A. Consequently the quality of the separator is practically unaffected by the chromatic aberration of the target image. The vertical target image, however, is distorted beyond recognition by the chromatic aberrations of the triplet (see phase space for + 0.5% $\Delta p/p$ in Fig. 3A). But the only effect is a restriction of the momentum bite. The momentum bite shown in Fig. 3C is produced by the combined effects of chromatic aberration and a 6° bending magnet behind the triplet. In the horizontal phase-plane the triplet is comparatively well-behaved.

The acceptances shown are slightly overfilled and this is taken into account in computing the effective solid angle. Some beam scattering will occur along the separator stage, but further collimation downstream, not shown, will remove background from this source. The beam transmission is 760μsr% for the high energy superconducting beam. For the room-temperature high energy channel and the intermediate energy channels we estimate the transmission to be about 400μsr% using inscribed squares as limiting apertures and the same target size. Typical matching section quadrupoles are 180cm long with a 15cm aperture excited to 18kG poletip field at 16 GeV/c.

Two Separated Beam Examples

The ideas presented in the foregoing sections can be assembled into several separated beam versions. A variation of the Sandweiss design[3)] incorporating the superconducting intermediate energy separator channel, with 7 GeV/c maximum momentum, would be 55m long. It would consist of the 27m long matching section with preliminary momentum analysis, the 16m long separator stage and a 12m long post-analysis section. In the latter section the unwanted particles would be intercepted on the beam stopper and the momentum reanalyzed within ±1% limits. The target would be viewed at an angle of 2°, so that the residual primary proton beam can be dumped without entering the matching section.

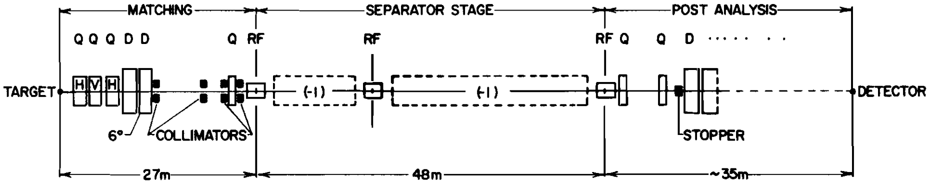

Fig. 4 High Energy Separated Beam Layout

For the high energy beam (see Fig. 4) one has to view the target at 0^o to obtain optimum yields, and the residual primary proton beam must be disposed of in the matching section. The separator stage for the superconducting separator is 48m long and for a room-temperature channel it would be 64m long. The post-analysis section would again reanalyze the beam momentum to within ±1%. But the disposal of muons will be a more critical problem, and we have therefore allowed about 35m for this section. The superconducting high energy beam would thus be 110m long.

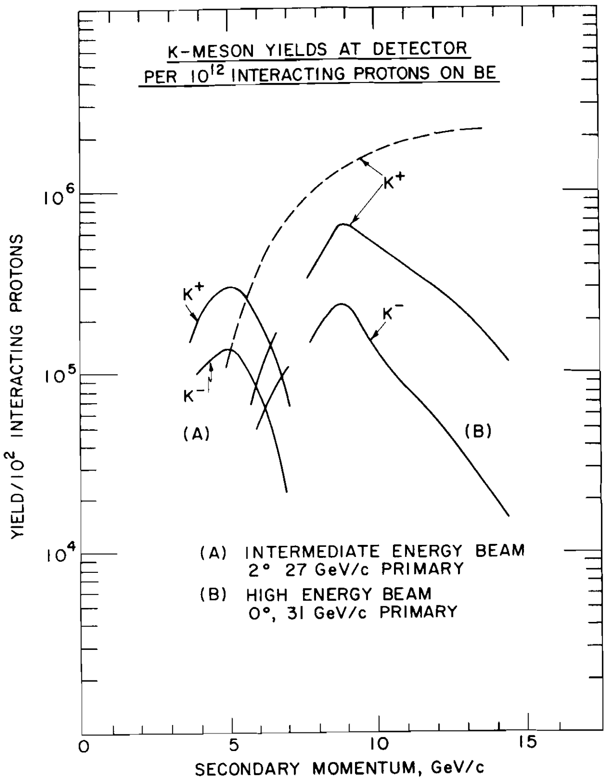

Fig. 5. K-meson yields at detector

Particle Yields

The yields of the superconducting versions of the high energy and intermediate energy beam were computed using the predictions of Sanford-Wang$^{10)}$ for protons on beryllium. The product of solid angle at the target and momentum bite is 760 μsr.%Δp/p for the high energy beam and 400 μsr.%Δp/p for the intermediate energy beam. The post-analysis section is designed to restrict the maximum momentum error to ±1%. In the absence of aberrations the separable vertical angular bite would be (S/p) times the peak transverse momentum of a cavity, with S taken from Fig. 1 and Fig. 2. This angular bite must be reduced, and the half width of the beam stopper increased, by the amount of the angular chromatic aberration of the separator stage optics (here estimated as 0.36 mrad/% Δp/p) and by the amount of the angular errors arising from the momentum-sensitivity of the RF phases for unwanted particles. The angular bite is transmitted past the beam stopper for only part of the RF cycle and the stopper transmission for this reduced angle ranges from 40-60%. With all these errors and losses, and due allowance for kaon decays, the yields of Fig. 5 are obtained at the detector. For the room temperature versions of these beams the yields would be lower by more than the ratio of the integrated deflecting fields. Even the superconducting separators at the conservative strengths assumed cannot separate the full solid angle provided by the beam.

Any gains in field strengths in the deflector would increase the yields. Also displayed on Fig.5 are the K^+ yields obtained if the high energy separator is strong enough to separate all of the beam acceptance, with 60% stopper transmission. For instance with a peak magnetic field of 360G and a doubly periodic deflecting structure with B/E_o = 120G/MV/m one would have $E_o \approx 3$ MV/m, increasing the yields by at least 50%, i.e. to about 10^6 K^+mesons per pulse at 9 GeV/c.

The intermediate energy beam yields of Fig. 5 can certainly be improved by exploiting more fully the round deflector apertures (rather than limiting by inscribed squares) and by decreasing the target size. Thus 10^6 $K^\pm$mesons per pulse can be obtained at 5 GeV/c as well.

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Note

Optimizations of RF separated beams have been carried out by different authors: H. Hahn and H. Halama, Proc. Accel. Conf., Washington 1967, and most systematically H. Schopper, VIIth Int. Conf. High Energy Accelerators, Yerevan, 1969, p.662. See also Ph. Bernard, H. Lengeler, V. Vaghin, P. Wilson ibid p.649.

DISCUSSION

H. LENGELER : Your angular acceptance of 760μ sterad seems very high to me.

H.W. FOELSCHE : Yes, the matching section gathers a huge solid angle by sheer brute force, and it fills the acceptance of the separator stage entirely. Its design is certainly not as conservative as it would have to be for a bubble-chamber beam. By permitting scattering in the separator stage, one accepts a small risk of compromising the beam purity, but one can deal with this background by collimating at image points of the scattering source further downstream, and by means of a good momentum analysis after the separator stage.

H. SCHOPPER : Has any further progress been made on wave guides lined with dielectric layer ?

H.W. FOELSCHE : No, the idea was not pursued at Brookhaven after Hahn had suggested substituting iris-loaded guides in the channel instead.