HIGH-QUALITY UNSEPARATED BEAMS

Don Reeder
University of Wisconsin

and

J. MacLachlan
National Accelerator Laboratory

ABSTRACT

This report contains a general discussion of design philosophy and a specific application to a 200 GeV/c and 120 GeV/c unseparated beam.

For the purposes of this study, we have investigated the properties of two unseparated secondary beams of high quality. They are based on a single design but have different production angles (2.5 mrad and 7.5 mrad), lengths, and thus different maximum momenta (200 GeV/c and 120 GeV/c).

They have the following characteristics:

1. Each beam allows two separate experimental setups by changing the polarity of the second set of bending magnets and retuning quadrupoles. No magnets need be physically moved.

2. Each leg of the Y is approximately achromatic at final focus.

3. The minimum momentum bite is 0.03% to first order. The maximum momentum bite is ±1% and acceptance is flat to this value. The above numbers are for one leg of the Y. The other leg is poorer by about a factor of 3.

4. The 2.5 mrad beam can transmit $\sim 2\times 10^{10}$ "diffracted" protons; it also allows a 2.5 mrad neutral beam of about 300 m in length.

5. Two additional quads and two additional bending magnets are required for the switching. Furthermore, two wide-aperture bending magnets are necessary to accommodate the neutral beam and the polarity change.

6. Each beam transports both positive and negative charged particles over range $0.1 \le p/p_{max} \le 1.0$, and each beam is independent of the operation of the other.

7. Each beam requires 11 quadrupole singlets. The small angle beam requires 12 bending magnets and the wide angle beam 10 bending magnets. These numbers include the special magnets discussed in 5 above.

The guiding philosophy in the beam design is expressed in the introduction. The rationale behind the particular choice of parameters, insofar as a rationale exists, is given below under elementary considerations. One additional constraint is geometrical in that no conflict in magnet positions can exist for the 4 beams in Area 2 and that the experimental areas should be separated by ~50 meters. Other quantities are arbitrary and all are subject to revision. The ray diagrams for the two tunes of each beam are shown in Figs. 1 and 2. First order solutions have been obtained using the TRANSPORT program. Some relevant parameters of the 2.5 mrad beam are presented in Table I. No claim is made that this design is optimal or complete. Indeed, several ideas and suggestions for improvement and extension of this study exist but require more time to explore. This is particularly true for the particle yields which may be improved by ~30% by optimization of length and location once final magnet and counter dimensions are fixed.

Elementary Considerations

For the beam shown schematically in Fig. 1, the horizontal magnification in the first stage is $M_H = f_B/f_F$. We define $(\Delta p/p)_{min}$ as the minimum momentum bite admitted by a slit whose width is equal to the horizontal image size. This condition may be written $(\Delta p/p)_{min}\, \theta\, f_B \approx f_B\, x_0/f_F$, where θ is the bend angle and x_0 is target size. Thus

$$(\Delta p/p)_{min} = \frac{x_0}{\theta f_F} . \qquad (1)$$

Note that this condition is independent of f_B. For $\theta = 45$ mrad, $x_0 = 1$ mm and $f_F \sim 65$ m, we calculate $(\Delta p/p)_{min} = 0.03\%$.

A condition on the horizontal back focal length can be obtained based on collimator considerations as discussed below; namely, that some horizontal magnification is desirable: $M_H \gtrsim 1.5$.

Instrumentation and Alignment

The proper instrumentation of a complex beam transport system can allow significant time savings in the tuning and diagnosis of the beam. However, the elements must function reliably in a "hot" environment and in some cases they are inconveniently located beneath 3 to 4 meters of shielding. It is recommended that a program of development and testing be instituted at NAL to investigate possible devices to solve these problems. The requirements imposed by beam design are:

1. Alignment and Monitoring of Magnet Positions. Typical tolerances on beam element alignment for the high quality beams are ~ ±10 mils in displacement and ~1 mrad in angular position. These values are derived from MacLachlan's[1] work and are meant

to be representative values. Possible candidates for monitoring systems are the NAL "hot wire" technique and the SLAC laser system.

2. Magnet Polarity Indication. Experience indicates that often at least one magnet is energized with incorrect polarity at the beginning of the tuning period. Current practice allows access to magnetic fields which can then be tested with a length of wire and flashlight battery. However, the length of beams at NAL and the inaccessibility of components do not allow this straightforward solution. It is recommended that each magnet have a remote indication of polarity, preferably by a direct field measurement.

3. Magnet Regulation. To attain good momentum resolution, the magnet currents must be stable to ~1-2 parts in 10^4. This requirement can be built into the power supplies or, alternatively, pole face windings can be used together within a servo system to correct field errors. In an achromatic transport system, it has often been possible to "track" the bending magnets by connecting them in series. When the bends are 300 meters apart, however, it may be uneconomical so to connect them. Also, we would prefer that in the final system the field itself is monitored rather than related voltages. For example, NMR or a pick-up coil might be used.

4. Beam Measurement. Measurement of beam profile or divergence at various points along the beam is necessary for tuning. Scintillation counter hodoscopes or proportional counters can be used to measure beam profile at a focus. Two such elements in coincidence can measure beam emittance directly to tune for a parallel beam, for example. These elements should be such that they can be inserted into the beam for measurement and remotely retracted out of beam when tuning is complete.

The number and function of the diagnostic elements depends on the detailed design. In this regard it is mandatory that the beam designer consider the tuning procedure and necessary instrumentation as an integral part of the design.

5. Slits and Collimators. In each beam there are two momentum collimators remotely adjustable over the range 0-10 cm to ~0.25 mm or better with remote readout. A solid-angle collimator is to be installed before the first quad, adjustable in the horizontal dimension with similar tolerances. This collimator can also be used to vary beam intensity without changing the tune. Other collimators may be needed depending on background problems.

Yields

The yields of charged particles are based on a thermodynamic model of Hagedorn and Ranft as calculated by White.[2] The single exception to the above statement is the yield of diffracted protons at beam energy which is calculated below. The results for our beams are presented in Table II and in Figs. 3 and 4. The yields for the second tune assume one wide aperture quadrupole similar to or identical to the 10 inch quads of ANL or BNL.

The yield of diffracted protons is based on the assumption of an exponential differential cross section

$$\frac{d\sigma}{dt} = \frac{\sigma_{e\ell}}{b} e^{bt} \simeq 100\, e^{10t} \frac{\text{mb}}{(\text{GeV/c})^2} .$$

The product of cross section times the aperture of the beam is

$$\bar{\sigma} = \int_{t_1}^{t_2} \frac{d\sigma}{dt}\, dt\, (\Delta\phi).$$

The horizontal beam divergence varies from 1.9 mrad to 3.4 mrad. Now $t = (P\theta)^2 = 0.04\,\theta^2\,(\text{GeV/c})^2$ where θ is measured in mrad. Thus $\bar{\sigma} = 10(e^{-1.4}-e^{-4.0})\Delta\phi$. At 55 m distant from the target, the displacement of the 2.5 mrad beam line from center line is 14 cm. So the azimuthal acceptance for a 10-cm aperture is $\Delta\phi = 10\text{ cm}/2\pi \cdot 14\text{ cm} = 0.114$. Thus $\bar{\sigma} = 0.26$ mb. Then the number of scattered protons is

$$N_p = \frac{N_0 A^{2/3} N_c \rho \sigma \ell}{A} ,$$

where N_0 = Avogadro's number, 6×10^{23} molecules/mole
- A = atomic weight = 184 for tungsten
- N_c = number of circulating protons = 10^{13}
- ρ = density = 19.3 gm/cm^3
- ℓ = target length = 4 cm.

Finally the number of scattered protons is $N_p = 2.12 \times 10^{10}$ per 3×10^{12} interacting protons. The required momentum bite to encompass the t range $-0.4 \le t \le -0.14$ is

$$\left(\frac{\Delta p}{p}\right) = \frac{3}{8}\,\theta^{*2} = \frac{3}{8}\left(\frac{p}{p^*}\,\theta\right)^2 = 150\,\Delta\theta^2 \approx 0.1\%,$$

where asterisk denotes c.m. quantities; the final value is easily attainable in the present beam design. It will be further increased by the Fermi momentum in the target nucleus, perhaps to as much as 0.3-0.5%.

Slits and Collimators

The performance and efficiency of collimators at energies > 50 GeV/c is obviously an important design consideration. The collimator functions by removing unwanted particles from the acceptance of the beam by:

1. multiple coulomb scattering

2. dE/dx
3. nuclear interactions
4. deflection in magnetized iron jaws.

Item 3 is the most important for hadrons; 1, 2, and 4 are applicable for muons.

One meter of uranium will affect a 200 GeV/c particle as follows:

1. θ_{rms} for multiple scattering = 1.7 mrad
2. $(\Delta E/E) \sim 1\%$ energy lost from ionization
3. if a hadron, it has a probability of surviving without interaction = 1×10^{-5},

that is, neither 1 nor 2 is particularly efficient in removing a particle from the beam. Typically the phase space dilution may range from 0.3 to 0.05. (Recall that beam emittance is about 1 mm-mrad.) Thus, it is desirable to make the collimator as long as possible and place it as close to target as possible.

Now consider a momentum collimator 1 meter in length. The acceptance of such a collimator is shown in Fig. 5. If W is measured in mm, then acceptance = W^2 mm-mrad.

For a very small slit the slit acceptance may compare unfavorably with the expected beam emittance of 1.6 mm-mrad. Opening the slit increases acceptance quadratically. Two extreme cases of containing the emittance are shown in Figs. 6a and b.

For a momentum collimator the case b is preferred, because it minimizes the resultant momentum bite. The band pass is as shown in Fig. 7. The exact shape of the band pass will depend, of course, on the specific design.

The moral of this story is that some horizontal magnification is desirable for a beam based on our input assumptions and that the momentum collimator should be as short as practicable.

REFERENCES

[1] J. MacLachlan, Charged Secondary Beams Using Main Ring Magnets, in Research Facilities Design Concepts, National Accelerator Laboratory Internal Report TM-181.

[2] M. Awschalom and T. O. White, Secondary Particle Production at 200 GeV/c, National Accelerator Laboratory FN-191, June 9, 1969.

Table I. Tabulation of Parameters of 2.5 Mrad Beam.

Quantity	Tune 1	Tune 2
θ_V vertical divergence at target	0.833 mrad	0.833 mrad
Y_0 target half size (vertical)	0.5 mm	0.5 mm
f_V^F vertical front focal length	33 m	33 m
M_V vertical magnification at clean-up slit	2.0	2.0
$\overline{M}_V$ vertical magnification at final image	0.9	1.0
θ_H horizontal divergence at target	0.520 mrad	0.44 mrad
x_0 target half size (horizontal)	0.5 mm	0.5 mm
ℓ_D dispersion at momentum collimator	4.6 cm/%	1.47 cm/%
f_H^F horizontal front focal length	67 m	–
M_H horizontal magnification 1.5 at momentum collimator	1.5	0.6
M_H horizontal magnification at final image	0.67	0.6
Beam size at final image (including final divergence for $\Delta p/p = 1\%$)	0.5 cm	0.08 cm
$\Delta\Omega$ acceptance (solid angle)	1.37 μ sr	1.15 μ sr
$(\Delta p/p)_{min}$ (1.5 mm min. slit width)	± 0.017%	±0.05%
$(\Delta p/p)_{max}$ (10 cm quads) with no loss	±1%	±1%
horizontal chromatic aberration at momentum collimator	1.9 mm/%	not calculated
overall length	463.3	413 m

Parameters for 7.5 Mrad Beam

$\Delta\Omega$ = 2.13 μ sr (Tune 1)		
$(\Delta p/p)$ similar to small angle beam		
overall length	281 m	231 m

Table II. Particle Yields $\times 10^{-3}$.

[Assume 3×10^{12} protons interacting and 0.05% momentum bite.
The yields given are for beam tune 1.
For tune 2 the yields are reduced by 20% ($p\bar{p}\pi^+\pi^-$) or ~10% (K^+K^-).]

Beam Momentum (GeV/c)	Prod. Angle (mrad)	p	$\bar{p}$	π^+	π^-	K^+	K^-
30	2.5	247	16.6	1233	1171	24.7	12.9
	7.5	383	20.1	1725	1438	80.6	36.1
50	2.5	565	13.3	1541	1336	58.6	20.5
	7.5	639	16.0	1438	1118	97.6	30.0
80	2.5	1808	4.9	1233	904	75.6	9.9
	7.5	895	5.1	511	383	79.9	12.8
100	2.5	4110	2.0	884	575	71.9	6.0
	7.5	799	1.3	160	128	54.7	3.9
120	2.5	7398	0.5	493	296	44.4	2.0
	7.5	575	—	58	36	14.0	0.8
150	2.5	12330	—	61.6	40.1	21.6	—
180	2.5	15166	—	0.7	0.2	—	—

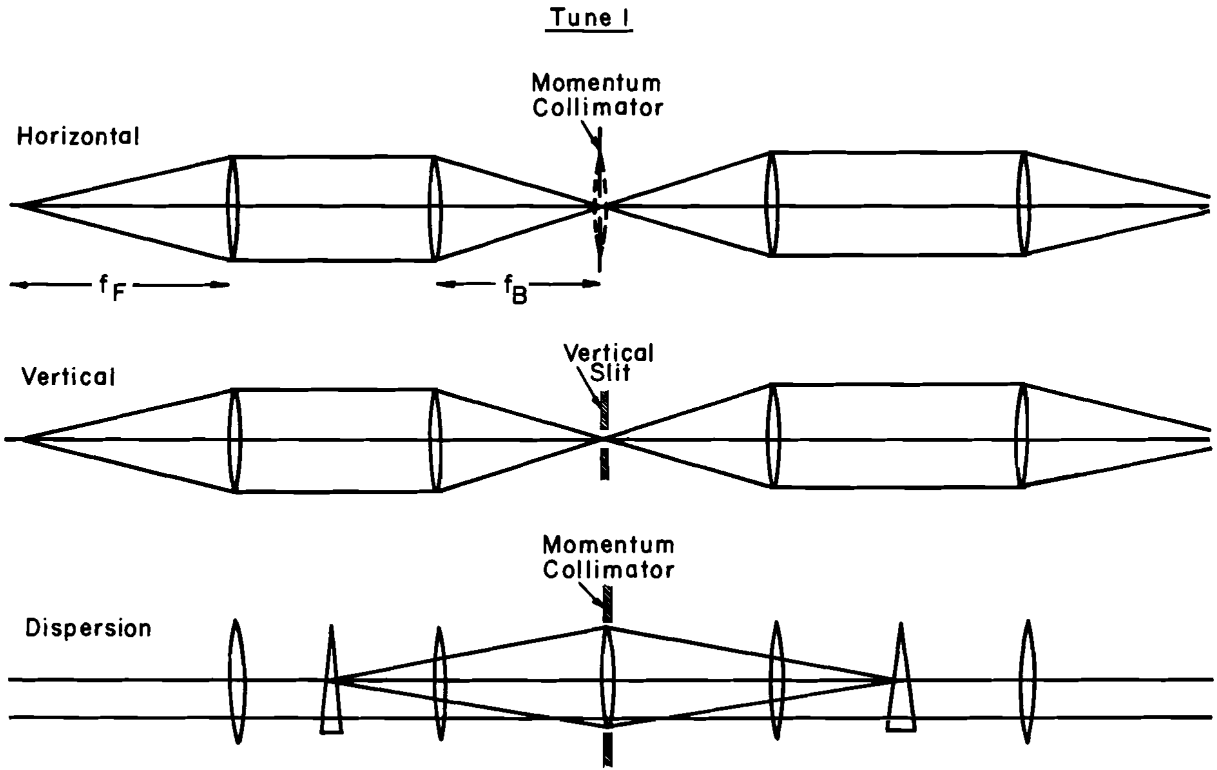

Fig. 1. Ray diagram of Tune 1 of unseparated beam.

Tune 2

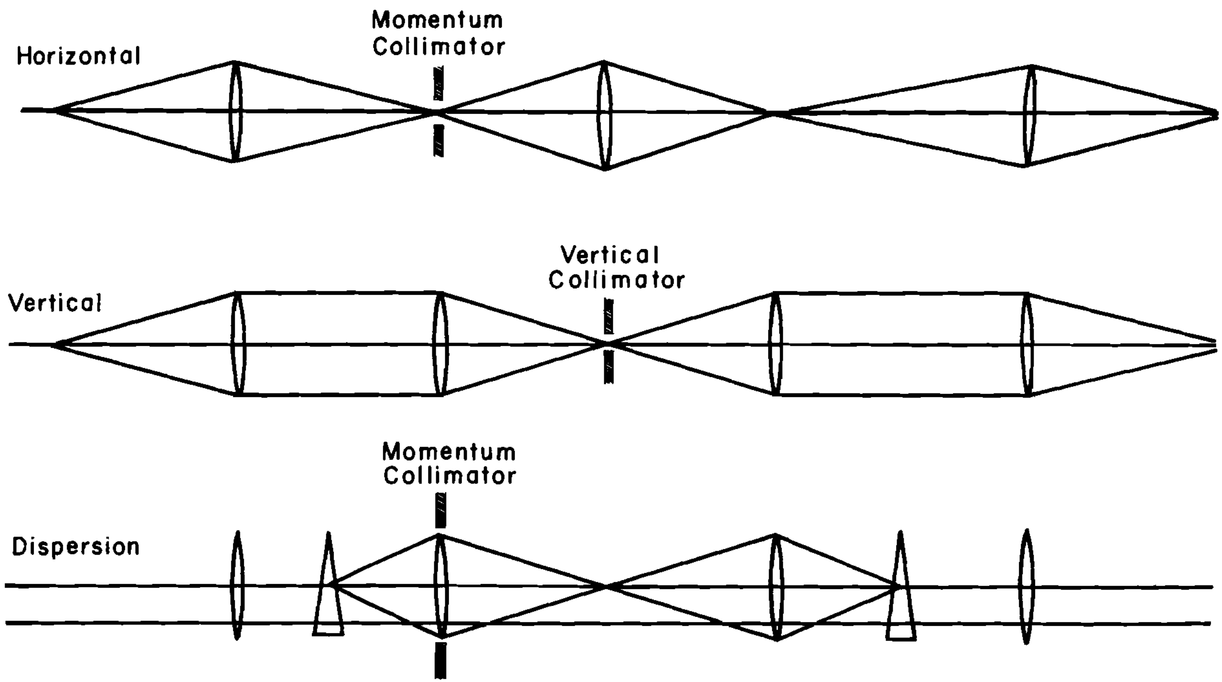

Fig. 2. Ray diagram of Tune 2 of unseparated beam.

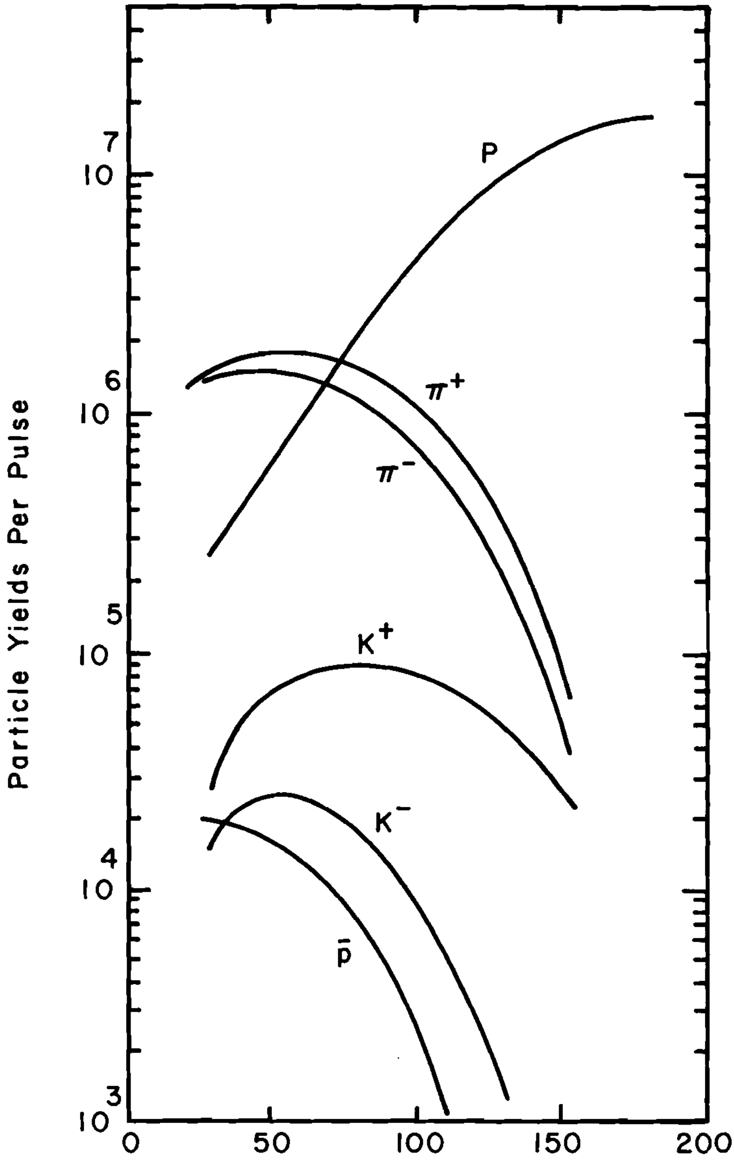

Fig. 3. Particle yields for the 2.5 mrad beam assuming 3×10^{12} protons interacting and a $\Delta p/p = 0.05\%$. The $K^{\pm}$ yields have been adjusted for decay loss using a beam length of 410 m.

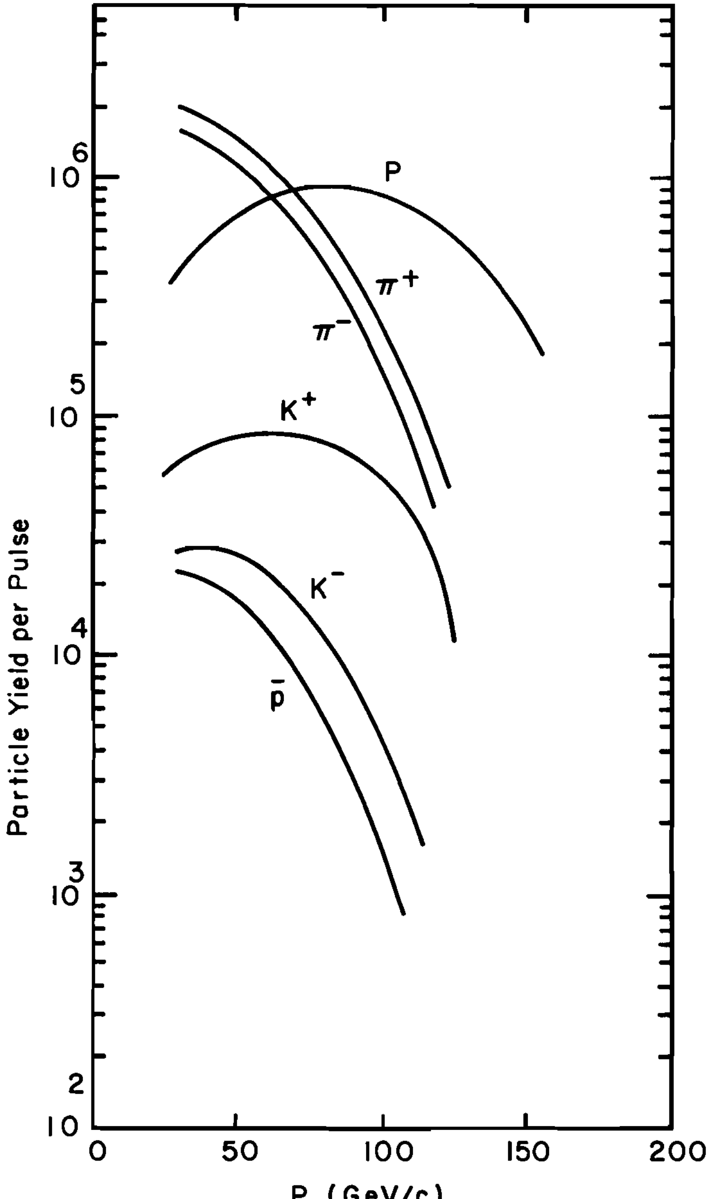

Fig. 4. Particle yields for the 7.5 mrad beam assuming 3×10^{12} protons interacting and a $\Delta p/p = 0.05\%$. The $K^{\pm}$ yields have been adjusted for decay loss using a 310 m long beam.

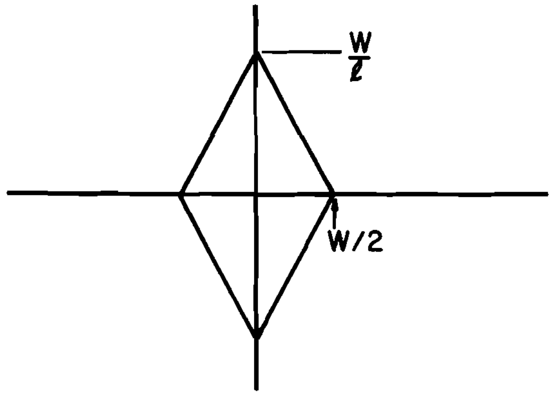

Fig. 5. Plot of acceptance of rectangular collimator of width ω and length ℓ.

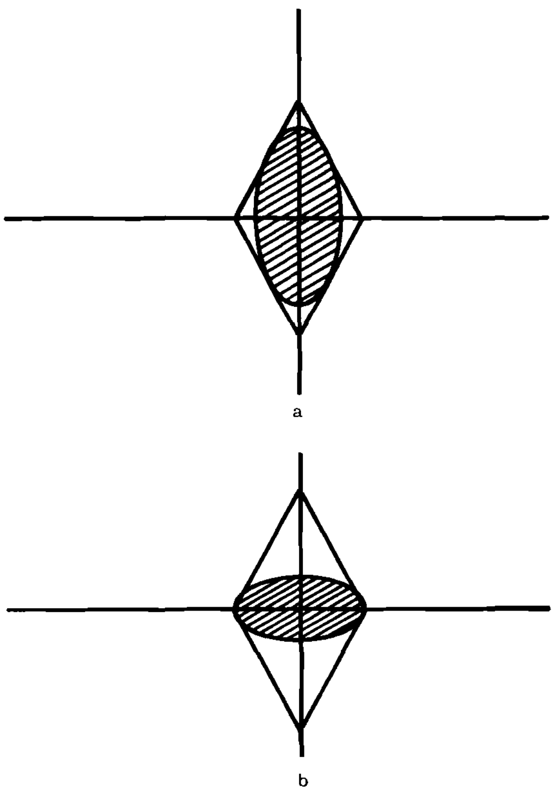

Fig. 6a and b. Plot of beam emittance and slit acceptance for R large and small where R = eccentricity of emittance ellipse.

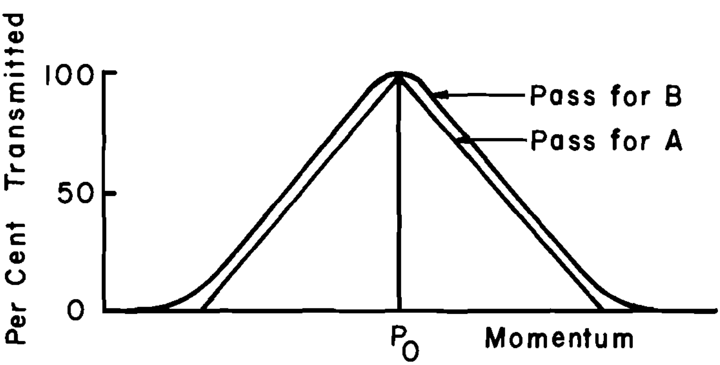

Fig. 7. Band pass of a momentum collimator for the two cases a,b as shown in Fig. 6a and b. (Schematic, not exact) P_0 is desired beam momentum.