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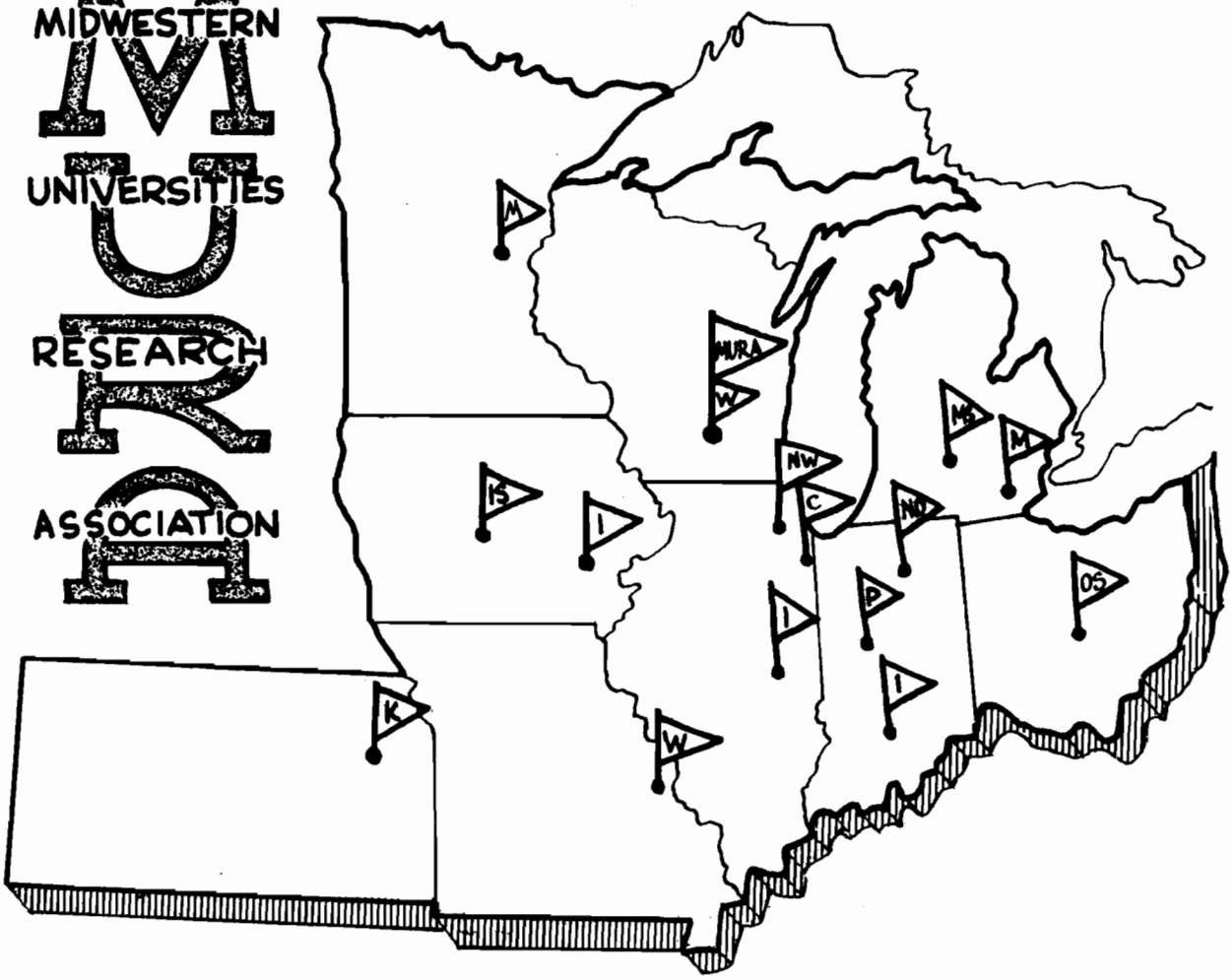


# ELECTROMAGNETIC SEPARATION OF SECONDARY BEAMS AT THE MURA ACCELERATOR

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REPORT NUMBER 584

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# ELECTROMAGNETIC SEPARATION OF SECONDARY BEAMS AT THE MURA ACCELERATOR

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August 15, 1960

## ABSTRACT

The problems of electromagnetic separation at MURA machine energies are examined. It is concluded that D. C. separation will handle all foreseeable needs, and poses essentially no special problems other than 1) precision tolerances on components, and 2) for the case of pulsed beams, a rather special target arrangement.

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# I. INTRODUCTION

## A. Secondary Beam Energies of Interest

A phase-space estimate of antiproton production[1] has given the qualitative result that $\overline{P}$ yields are appreciable from nearly zero lab momentum up to close to the kinematic limit.

The kinematic limit, in turn, approaches the machine energy. (12 Bev/c $\overline{P}$'s at 15 Bev machine energy.) The effect of Fermi motion, not included in these calculations, will be to give an appreciable yield at the "kinematic limit."

For K mesons, the same qualitative feature will hold, since for these the center-of-mass momentum can be even greater.

For separation purposes, then, we must contemplate separation of K's ranging up to about 14 Bev/c and $\overline{P}$'s up to 12 Bev/c, (for a 15 Bev machine).

## B. D. C. vs. R. F. Separation, and Separated vs. Unseparated Beams

The chief facility the MURA machine can provide will be intense, separated, secondary beams. The corresponding unseparated beams will in many cases be too intense to permit electronic identification of the particles. Even where this is not true, the relative cleaness of an experiment that starts with a purified beam will frequently justify the loss in intensity attendant upon separation. (In round numbers, one can get perhaps tenfold more $\overline{P}$'s and one hundredfold more K's, by not separating, provided the momentum band accepted is increased.)

There will certainly be experiments which do not need separators, but there will also certainly be a large class which will.

The next question is whether to use R. F. or D. C. separation. The big disadvantages of R. F. are that the system must be pulsed and that the aperture is necessarily small. (We refer to operation in the 10 to 20 cm wavelength region.) There is little doubt that D. C. separation is preferable if it can be done at all.

## II. D. C. SEPARATION

### A. Momentum Bite, Transmission, Ratio of Separation to Image Size

Most of our arguments will be based on extrapolation from existing practice, in particular from the 1.17 Bev/c $K^-$ beam at Berkeley.[2]

In this beam the momentum bite was 2.5%.

In a parallel-plate separator, the horizontal and vertical motions are independent to first order. Thus there is no special problem in obtaining any desired momentum bite, provided it is not so large that chromatic aberrations become serious, and interfere with the separation.

In what follows, we shall assume 2 1/2% momentum bite. In a precision experiment, one would not want much more than this; a smaller momentum bite is easy to obtain, the chief disadvantage being the reduced intensity.

The transmission of such a separator is determined by: the entrance solid angle, the momentum bite, any losses encountered in either horizontal or vertical motion in going through the system, and, for K's, decay in flight.

In what follows we shall assume the entrance aperture to be the same (2" x 5.5") as in the beam of ref. 2, so that the solid angle varies as $\frac{1}{f^2}$ where f is the focal length of the first lens. The vertical losses were $\approx$ 10% per stage. We will find these remain the same or get smaller as we go up in momentum. The horizontal losses were zero, and will remain zero.

The variable factors in the transmission will therefore be the focal length, and, for K's, the overall length. For K's, we have

$$T \sim \frac{1}{f^2} e^{-\frac{n(\ell+2f)}{(p/m)c\tau}} \tag{1}$$

where:

T = transmission

n = number of stages

f = focal length

$\ell$ = separator length

P/M = = Momentum/rest mass

$\tau$ = $1.2 \cdot 10^{-8}$ sec., ($K^{\pm}$ lifetime)

The essential relation is the ratio of separation to image size. This is at a maximum for a parallel beam through the spectrometer, and is independent of the magnification. We assume unit magnification for simplicity, and then have

$$S_{12} = \frac{E\ell f}{\delta x}\left[\frac{1}{p}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) \simeq \frac{M^2}{p^3}\right] \tag{2}$$

where:

E = electric field

$\delta x$ = image size

$\beta_{1,2} = V_{1,2}/c$ .

For separation from $\pi$'s, we may replace $\beta_1 = \beta_\pi$ by 1, $\beta_2$ by $\beta$. The function on the right then goes like $M^2/p^3$ for $p \gg M$.

The problem is then how to fulfill the condition

$$\frac{E\ell f}{\delta x} \sim p^3$$

as we increase the momentum.

B. Ways and Means of Going to Higher Momenta

1. Electric Field Increase

J. Murray has recently succeeded in holding field gradients up to 200 KV/cm over apertures of several inches, using a heated glass electrode. We assume tentatively, that this technique is practical. We have therefore

$$E \simeq 3E_0$$

(The subscript zero will refer in all cases to the beam of ref. 2.)

2. Increase of Length

This of itself does not help. The increase in length must be accompanied by an increase of focal length or a decrease in image size. This is because the beam spreads vertically by an amount $\left(\frac{\delta x}{f}\right)\ell$ in going through the separator. At present this gives a loss of about 10% per stage, or $\approx$ 30% in a three-stage separation. Thus doubling $\ell$ would result in about a factor of 2 loss in yield, while raising the momentum only by $2^{\frac{1}{3}} = 1.26$. Eventually, this loss goes as $\frac{1}{\ell}$, per stage, and so as $\ell^{-3}$ for three stages, whereas the momentum would go only as $\ell^{\frac{1}{3}}$.

Also, for K's, the increase in $\ell$ means more decay in flight.

3. Increase of Focal Length

This helps the separation, but hurts the transmission as $1/f^2$. Also, for K's, it increases the total length. On the other hand, f must increase as p increases, simply because the quadrupoles saturate.

4. Decrease of Image Size

This is the only variable, outside of electric field, that helps the separation without hurting the transmission.

a. In order to decrease the image size, it is necessary to reduce the aberrations of the optical system:

i) Spherical Aberration

This is caused by faulty design, in the case of quadrupoles, and can certainly be reduced greatly.

In the case of bending magnets, the spherical aberration can be shimmed out to any desired degree by a sufficiently complex set of current shims.

ii) Chromatic Aberration

This may be removed to first order in one of two ways.

A) by a wedge absorber (this was suggested by U. Camerini).

B) by cancellation against a deliberately introduced spherical aberration.

In method A), the wedge is placed in the first slit. A double focus (horizontal and vertical) is effected at this slit. Because of the dispersion of an initial bending magnet, each momentum is focused to a different lateral

position. Because of the chromatic aberration, each momentum is also focused at a slightly different distance from the lens. The slit is cocked horizontally, so that its effective position is at the actual focus for each momentum.

The wedge then brings all particles to the same momentum; since the wedge is at a focus, the affect of its scattering is minimized.

The subsequent separators then reproduce this same cocked focus, with no further trouble from chromatic aberration.

The required absorber is in all cases less than a nuclear mean -free path. The physical length of the absorber might be troublesome at higher momenta, however.

In method B), a horizontal focus is made at the second quadrupole. Because of the dispersion, the momentum is a well-defined function of transverse position at this point. The vertical focal length of the second quadrupole is deliberately made a linear function of transverse position, (a form of spherical aberration) in just such a way as to compensate for the variation of its focal length with momentum (chromatic aberration). This brings all momenta to a sharp vertical focus at the first slit. The process is then repeated in each subsequent stage of separation. In the beam of ref. 2, the image size was due about equally to multiple scattering in the Bevatron thin window, and to the combined effects of all aberrations.

The image size due to aberrations was thus about 0.100".

It seems clear that this can be reduced by a factor of three with ease, and by a factor of ten by diligent attention to detail.

b. The target size must also be reduced. We consider a target .015" high; folded with the above aberrations (.010"), we get .018" for the image size, about ten times smaller than in the beam of ref. 2.

We assume then

$$\delta x \simeq \frac{1}{10} (\delta x)_0$$

## C. Discussion and Examples

We must now decide how to vary $\ell$ and f. We will keep f as short as is practical (i.e., so as not to overwork the quads) and adjust $\ell$ to make up the necessary $f\ell$ product as required by the separation criterion. We can then examine the result, to see if the transmission is optimized. We take as a practical minimum for f :

$$f = (f_0 = 10') \left(\frac{p}{1.7}\right)^{\frac{1}{2}} \tag{3}$$

based on the fact that 10' is about right at 1.7 Bev/c, and we can scale the orbits if we increase the focal length and the physical length of the quadrupole as $p^{\frac{1}{2}}$. ( $\frac{\partial H}{\partial x}$ is held constant.)

We thus have, for K's,

$$\frac{E\ell f}{\delta x\, p^3} = \frac{E_0 \ell_0 f_0}{\delta x_0\, p_0^3}$$

$$\ell = (\ell_0 = 20') \left(\frac{E_0}{E} = \frac{1}{2}\right) \left(\frac{\delta x}{(\delta x)_0} = \frac{1}{10}\right) \left(\frac{f_0}{f} = \left(\frac{1.7}{p}\right)^{\frac{1}{2}}\right) \frac{p^3}{(p_0 = 1.17)^3} \tag{4}$$

$$\ell = 0.54\, p_{Bev/c}^{5/2} \quad \text{(FEET)}$$

For K's

| $p_K$ | $\ell_K$ | f | 1 + 2 f | $L_{Decay}$ |
|---|---|---|---|---|
| 5 | 30' | 17' | 64' | 121' |
| 10 | 171' | 24' | 219' | 242' |
| 15 | 470' | 30' | 530' | 362' |

For $\bar{p}$, we insert a factor $\left(\frac{M_K}{M_{\bar{p}}}\right)^2 = .28$ on the right side of (4), so that

$$\ell_{\bar{p}} = .28 \times .54\, p^{5/2}$$

$$= .15\, p^{5/2} \text{ feet.}$$

| $p_{\bar{p}}$ | $\ell_{\bar{p}}$ | f | 1 + 2 f |
|---|---|---|---|
| 5 | 8.4' | 17' | 43' |
| 10 | 48' | 24' | 96' |
| 15 | 132' | 30' | 192' |

We have the remarkable result, that our most difficult task, that of separating K's from $\pi$'s, at 15 Bev/c, is possible with a separator only $\frac{530'}{362'} = 1.46$ decay distances in length. For two stages, comparison to the

1.17 Bev/c $K^-$ beam of ref. 2 gives

$$T/T_0 = \frac{(10)^2}{(30)^2} \frac{e^{-1.92}}{e^{-4}} \simeq \frac{1}{3}$$

The loss is hardly worth mentioning.

The above results contained some fairly optimistic assumptions. If, however, we give only a factor 3 gain in $\delta X$ and none in E, a much more conservative set of figures, then, by similar methods, we find separation possible at 3.5 Bev/c for K's, and 5 Bev/c for antiprotons.

D. Plate Parallelism Tolerance

If the electric field, averaged over the path of the particle, varies in fractional amount $\left(1-\frac{1}{\beta}\right)$, the $\pi$'s will be put on the K slit, a complete disaster. If we demand the $\pi$'s move by no more than one-tenth of this amount, we have

$$\frac{\langle \Delta E \rangle}{\langle E \rangle} \leq \frac{1}{10}\left(1-\frac{1}{\beta}\right) \simeq \frac{1}{10}\,\frac{1}{2\gamma^2}$$

also $\frac{\langle \Delta E \rangle}{\langle E \rangle} \simeq \frac{\langle \Delta D \rangle}{\langle D \rangle}$ where D is the plate spacing. Finally $\langle \Delta D \rangle \leq \frac{\langle D \rangle}{20\gamma^2}$

For K's at 5 Bev/c $\langle \Delta D \rangle \leq .0012''$

at 10 Bev/c " .0003"

at 15 Bev/c " .00014".

This may be interpreted as the difference between plate spacing at the two sides of the beam.

This tolerance is difficult, but not impossible.

There is a corresponding tolerance on non-uniformity of the field due to fringing, $\frac{\langle \Delta E \rangle}{\langle E \rangle} < \frac{1}{20\gamma^2}$ = .005% (15Bev/c) which will require careful

attention. However, it is not a fundamental limit. If the plates are made wider, the fringe field goes down accordingly.

The same comments apply for the magnetic field.

The field uniformity tolerances, while difficult, can presumably be met, by careful design and testing.

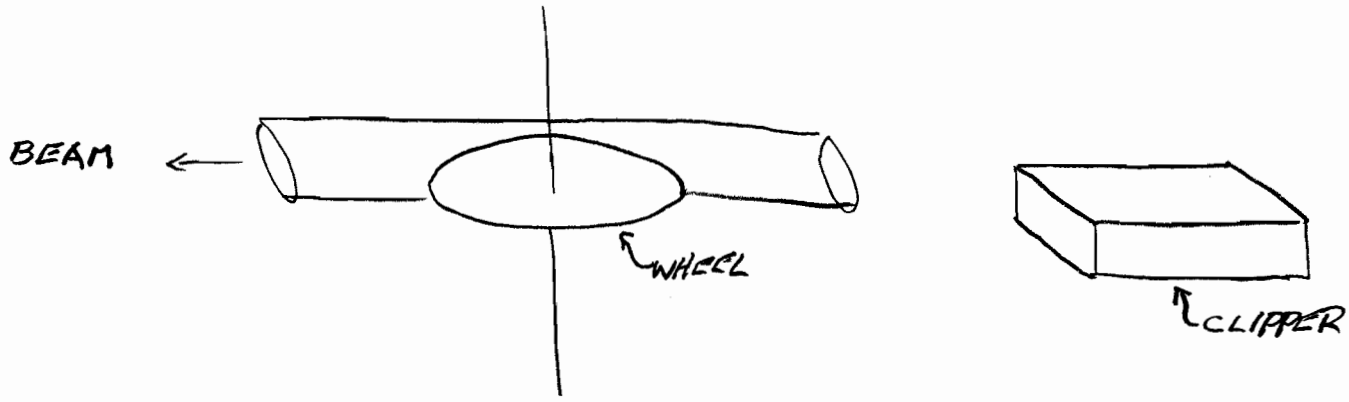
## III. TARGETING FOR SEPARATORS

### A. Target Heating, (D. C. Operation)

We consider a target .015" in height, since that is thin enough for all cases considered.

As for the horizontal dimension, about 0.5" or less is required, on the following grounds: we wanted to diminish the chromatic aberration by a factor of ten. To do this the horizontal image must be equal to or less than one-tenth the horizontal aperture $\approx$ quadrupole aperture $\approx$ 5". Hence, the horizontal image must be $\frac{1}{2}$" or less in horizontal dimension.

A thin wheel satisfies these requirements, provided the $\frac{1}{2}$" horizontal size requirement is fulfilled by clipping the beam so that nothing strikes it more than $\frac{1}{2}$" from the edge. Alternatively, a secondary image could be formed outside the accelerator and collimated there.




We now see how fast we must spin the wheel. The mean power dissipated in the target is essentially the ionization loss accompanying one nuclear mean-free path, or about

$$\Delta E \simeq 2\left(\Delta R \simeq 30 A^{1/3} \simeq 80\ \gamma/\mathrm{cm}^2\right) \simeq 160\ \mathrm{Mev} \quad (\mathrm{CARBON})$$

$$P = \frac{\partial n}{\partial t}\,\Delta E$$

$$= (2.10^{14}\ \text{Protons/sec}) \times (160\ \text{Mev})$$

$$= 3.2 \cdot 10^{22}\ \text{ev/sec}$$

$$= 5 \cdot 10^{10}\ \text{erg/sec}$$

$$= 5000\ \text{watts}$$

$$= 1200\ \text{calories/sec}$$

In such a thin target, the cooling must be either by radiation or by physically removing hot material from the beam. Conduction is out of the question.

The area required to radiate this much power is

$$A = \frac{P}{\epsilon\,\sigma\,T^4}$$

$$A = 22\ \mathrm{cm}^2 = 3.4\ \text{sq. in.}$$

$T = 3000^{\circ}$

$\sigma = 5.7 \cdot 10^{-5}\ \mathrm{erg/cm^2\ sec}$

$\epsilon$ = Emissivity; (Use $\frac{1}{2}$)

Thus a rectangle $\frac{1}{2}$" x 3.4" (x 2 sides!) would seem to do. There is catch, however. The loading would probably not be uniform, and so it might melt. We are thus probably forced to use a wheel.

The time constant for cooling a thin slab by radiation is

$$\tau = \frac{T\, c\, \rho\, t}{P_{Rad.}}$$

$$= 2 \text{ seconds (carbon)}$$

C = specific heat

$\rho$ = density

t = thickness

Then, if we spin our wheel at several revolutions per second, all parts of the rim will run at the same temperature, and the whole rim area contributes to A. A wheel several inches in radius would seem to work nicely.

B. Target Heating, Pulsed Operation

What we mean by this is, we store the beam, for say 10 seconds, then dump it on a target in a millisecond or less, (for bubble chamber operation, for instance).

This poses a much more severe target heating problem, since the instantaneous power is up by 10 sec/$10^{-3}$ sec = $10^4$ over the 5 KW average. This would vaporize the portion of the target in the beam.(12,000 calories, compared to $\simeq$ 1500 calories to melt 1 gm. of carbon. About $\frac{1}{2}$ gm. is required to be in the beam in order to dump the beam in 1 millisecond.)

The target material must therefore be shot through the beam at such a rate that about 10 gm. are exposed, in one millisecond. For our wheel, at a radius of a few inches (in order that the target not appear too long in the beam direction), we obtain

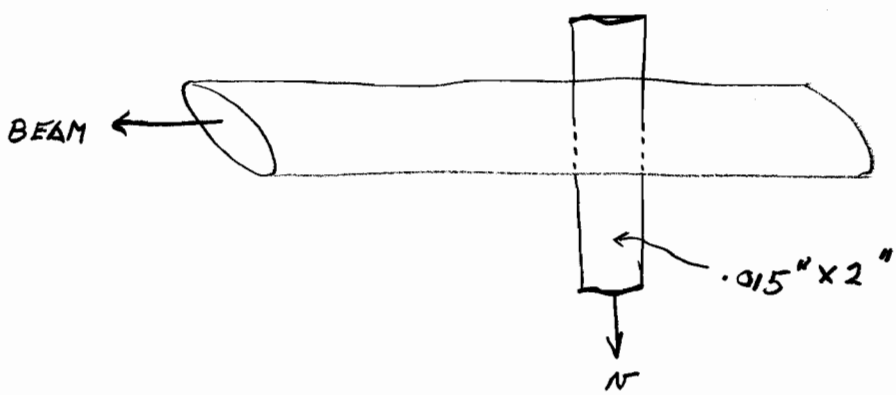
$$.015'' \times 0.5'' \times (2.54)^2 \times (\rho \simeq 2)\ v = 10\,gm/10^{-3}\,sec$$

$$v = 10^5\ cm/sec$$

$$\frac{v^2}{r} = (10^5)^2 \frac{1}{10} = 10^9\ cm\ sec^{-2} = 10^6\ "g"$$

This is clearly impossible. The matter must move in a straight line.

We therefore contemplate firing a ribbon vertically through the beam, and (reluctantly) tip the separator over on its side (this solution was proposed by K. R. Symon and A. Galonsky):




The target shown has the required $\frac{1}{2}$ gm. in the beam. The velocity must be at least

$$v = \frac{10\ gm\ (\frac{1}{2}'')}{(\frac{1}{2}\ gm)\ 10^{-3}\ sec} = 10^4\ IN./SEC.$$

$$= 830'/SEC.$$

for a millisecond, $\approx$ 10" of tape pass through.

This solution appears feasible, although certainly awkward. We conclude that pulsed operation is possible, in the millisecond region. Perhaps a better solution can be found.

C. Target Length

The target must not be too long because of the finite entrance aperture; when viewed from the top of the aperture, the target looks thicker in the amount

$$\delta' x = \frac{aL}{2f}$$

a = vertical aperture ($\simeq$ 2")

L = target length.

Our worst case is when f is small, say 10'. Then if we set

$\delta' x \lesssim \delta x$ = .015",

$$L \lesssim \frac{2\,(120'')\,(.015'')}{2''} = 1.8'' .$$

This case corresponds to 1 - 2 Bev/c, at which momenta $\delta x$ could be relaxed. For the higher momenta, $f \sim p^{1/2}$, and so $L \sim p^{1/2}$ is allowed; thus targets can be the usual 4 to 6" long in most cases, if desired. There seems to be no problem.

D. External vs. Internal Target

To obtain efficient targeting in an external beam, we must bring the beam down to a focus .015" high. Since the beam is $\frac{1''}{2}$ high inside the machine, where it is confined with rather strong lenses, this is difficult. We would need a lens of focal length $\frac{.500''}{.015''}$ = 33 - fold shorter than the

machine lenses. This perhaps is not impossible, but then the angular spread would be $\simeq$ 33 milliradians, and the target should be no longer than $.015'' \times \frac{1000}{33} \approx 0.5''$ which is again inefficient.

Thus efficient targeting for separators seems impossible with an external beam, unless the spread in phase space of the external beam is smaller than that for the internal beam.

The internal beam seems to offer no great disadvantages, provided the target is in a truly field-free region. The accessibility is not as bad as one might at first think; the focal length limitations of quadrupoles keeps the first quad rather far away from the target, so that several beams may be placed side by side.

## IV. CONCLUSIONS

We conclude that reasonable extrapolation of existing D. C. separator techniques, with careful attention to tolerances, will enable separation of K's and $\bar{P}$'s from $\pi$ 's to be achieved at all energies of interest to MURA.

## REFERENCES

[1] M. L. Good, Memo, June 23, 1960.

[2] P. Eberhard, M. L. Good, and H. K. Ticho, UCRL-8878.