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SOME HIGH RESOLUTION TECHNIQUES FOR USE WITH NEGATIVE ION BEAMS*

by

J. E. Spencer and H. A. Thiessen
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico

ABSTRACT

The 800 MeV linac at LAMPF provides simultaneous beams of protons and negative hydrogen ions by accelerating separated bunches on successive half-wavelengths of the rf cycle. Use of the negative component provides some unique advantages for determining various experimental information as well as for beam diagnostic purposes. Here we describe some techniques which can be used to provide absolute determinations of the beam current and beam energy. Since the energy is constantly available during the course of an experiment, it can also be used as part of a feedback loop associated with either the experiments or with the rf cavities of the linac. A related discussion concerns techniques which rely on the negative ion beam for performing accurate experimental ray tracing at LAMPF energies. This can be a particularly useful tool for achieving optimal performance from very high resolving power systems.

I. INTRODUCTION

Since the possibility of accelerating negative hydrogen ions (H^-) at LAMPF was shown to be feasible,[1] it has been obvious that the benefits far outweight the inconvenience. Although the idea has some interesting applications associated with coherent beam breakup processes in high current linacs, its primary purpose at LAMPF is that it allows multiple experimental areas which can be utilized completely independently of one another. Figure 1 shows the layout of the LAMPF switchyard. The higher intensity proton line, designated Line A, has several associated secondary meson lines and experimental areas. The H^- beam line has three additional experimental areas which also function simultaneously by using thin, charge-stripping foils or filaments to successively strip electrons off that fraction of the H^- beam required for each of the different experimental areas, designated in the figures as Beam Areas B and C.

Here we will discuss an application which uses thin foils with fine holes or slots in them which function as anti-strippers, i.e., to strip away portions of the beam which one does not want transmitted to the experimental areas. Such foils can be used to provide very narrow collimation of a beam with virtually no resulting halo. From this standpoint the alternative of using electric dissociation in a shaped magnetic field is less satisfactory. However, foil endurance tests[2] have not yet been carried out for the power densities involved here. When such foils are properly incorporated into an ion-optical transport system they can be used to provide independent tuning of the (x,y), (θ,ϕ), and δ phase space variables to within extremely narrow limits. Such control can then be used either to limit the range of variation of these variables at the target during an experiment or to systematically tune a high resolution system prior to an experiment.

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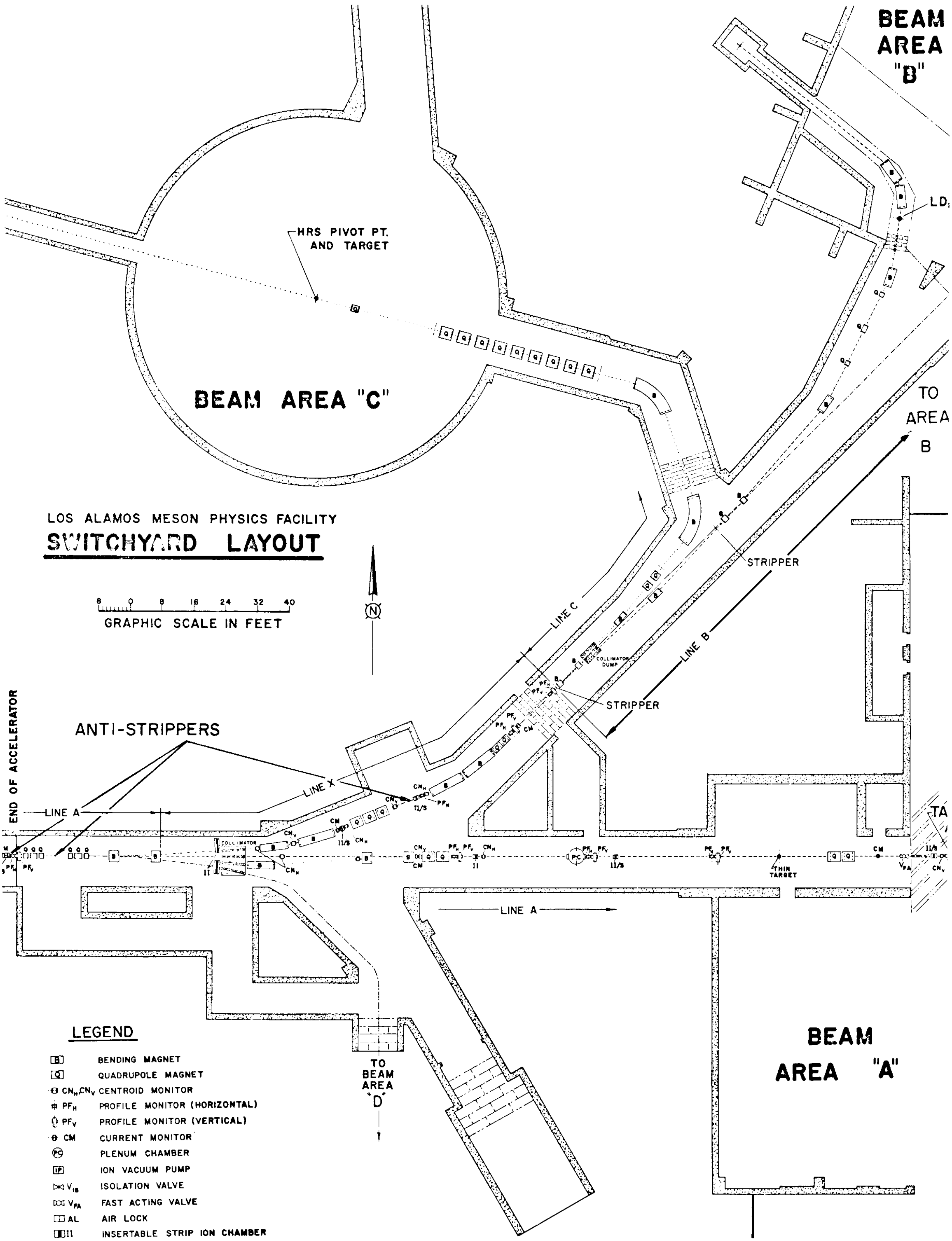
BEAM AREA "B"
HRS PIVOT PT. AND TARGET
BEAM AREA "C"
TO AREA B
LOS ALAMOS MESON PHYSICS FACILITY
SWITCHYARD LAYOUT
8 0 8 16 24 32 40
GRAPHIC SCALE IN FEET
N
STRIPPER
LINE C
LINE B
COLLIMATOR DUMP
STRIPPER
END OF ACCELERATOR
ANTI-STRIPPERS
LINE A
LINE X
COLLIMATOR
THIN TARGET
LINE A
TO BEAM AREA "D"
BEAM AREA "A"
LEGEND
B BENDING MAGNET
Q QUADRUPOLE MAGNET
CN_H,CN_V CENTROID MONITOR
PF_H PROFILE MONITOR (HORIZONTAL)
PF_V PROFILE MONITOR (VERTICAL)
CM CURRENT MONITOR
PC PLENUM CHAMBER
IP ION VACUUM PUMP
V_IS ISOLATION VALVE
V_FA FAST ACTING VALVE
AL AIR LOCK
II INSERTABLE STRIP ION CHAMBER

Fig. 1.

Another application discussed here entails the use of a 180° spectrometer to collect the stripped electrons with a split-Faraday cup. Since the velocity of the electrons is essentially the same as that of the protons, a measurement of the electron energy is equivalent to a measurement of the proton energy. Similarly, a measurement of the total stripped charge is equivalent to a measurement of the proton current transmitted to the experimental area (gain = 2). A typical example indicates that one can replace an 800 MeV proton Faraday cup with a 435 keV electron cup. Furthermore, since all of this information is available on a pulse-to-pulse basis during the course of an experiment, it can be included as part of a feedback loop to provide time-of-flight information or better energy resolution by phase or amplitude compensation at the end of the accelerator.

II. EXPERIMENTAL RAY TRACING

In any beam transport or spectrometer system there may be any number of contributions to the observed resolution beyond those predicted solely on the basis of the ion-optics. While some of these contributions can be isolated and studied analytically or with Monte Carlo methods, many cannot. As a consequence, the actual properties of a real system generally have to be determined empirically. When very good resolution is required, the various short term possibilities such as misalignments and their effects on the resolution make it advisable to have a means of tuning these systems which can include day-to-day changes. In this section we describe a flexible means of tuning a beam transport system having a desired momentum resolving power of 10^5. It relies on the use of the negative ion beam to perform accurate experimental ray tracing.

Since neither the intensity nor the phase space of the full beam from the accelerator is adequate for these purposes, it is first necessary to prepare a low intensity, high resolution pencil of rays. By measuring the response of the system to this pencil, at key locations along the beam line, as it is systematically scanned over the full phase space of the beam, one can optimize the response according to some prescribed objective function. The overall procedure can be summarized into roughly six steps:

1. First prepare a zero phase space beam (pencil) at the stripper by using anti-strippers at appropriate upstream locations in the switchyard.
2. Having set all beam line magnets at values appropriate to the desired energy and dispersion, etc., adjust their currents to get the beam centered throughout the system.
3. Scan the pencil over the phase space of the full beam to be used in the experiment by using steering magnets in the switchyard.
4. For each point in the beam scan, measure the centroid of the beam at certain key locations along the beam line. From these measurements derive a figure of merit such as used in the ray tracing design of the beam line or spectrometer system.
5. Calculate a set of changes in the magnet currents that will improve the figure of merit using an on-line computer.
6. Repeat items (3) and (4) above to check the corrections and then repeat (5), if necessary, as the next step in an iteration procedure.

For such a method to be effective one needs to be able to make measurements with very good spatial resolution as well as to be able to easily tailor both the intensity and the phase space of the incident beam. These are not simple problems especially at LAMPF energies. Furthermore, it is not possible to circumvent them by using radioactive sources because of their too low magnetic rigidities. A way of doing these things has been described elsewhere,[3] here we concentrate only on item (1).

III. BRIEF DESCRIPTION OF LAMPF SWITCHYARD

Figure 1 shows the overall layout as well as the disposition of the anti-strippers which will be used to produce a nearly zero emittance beam having a momentum spread on the order of 10^{-6}. The first of these is located at the end of the accelerator, directly in front of the first quadrupole triplet. When in use it will normally consist of a 1 mg/cm^2 carbon foil with a small hole in its center having a diameter on the order of a few mils. For this thickness the H^o contamination has been estimated[2] to be less than one in 10^6 which can easily be handled by the rad-hardened beam plumbing. The stripper/anti-stripper mechanism at each location will allow any of 12 different foils to be remotely selected and positioned according to the application.

At the location of the first anti-stripper the beam is diverging slowly from a waist a few meters back into the accelerator. The triplet refocuses the beam, bringing the next x and y waists together midway between it and the next triplet. The second foil, which is identical to the first, is placed at that location. The next two magnets in the line are 2° bending magnets which magnetically separate the two beams with the protons continuing down Line A together with the stripped proton current. These two magnets are separated so that a macropulser can be added between them should the need arise. The remaining dipoles in Line A then deflect the proton beam back along the original beam direction prior to entering experimental Area A. Except for the initial 180° phase difference between the two beams entering Line A there is essentially no difference between proton bunches passing through these magnets. Since the incident beam momentum spread is expected to be $\delta p/p = \pm\ 0.26\%$ and the incident angular spread in both directions is $\geq \pm\ 0.30$ mr for over 96% of the beam at the different strippers, figures 2 and 3 verify this for the case of 800 MeV protons.

The unstripped H^- beam is bent an additional 18.5° away from Line A by two more bending magnets in Line X. Since this line is supposed to be achromatic at the stripper, located at the beginning of Line C, the third anti-stripper, which has a fine slit in it parallel to the y direction is located just after the achromatizing triplet as shown in Fig. 1. A justification of these locations is given in the next section.

IV. PREPARATION OF THE ZERO PHASE SPACE BEAM

At these particular locations, the three anti-strippers can be made to function independently of one another, i.e., the first one defines the effective object size; the second, defines the effective angular divergence; and the third, the momentum bite of the resulting beam, so that none of them are redundant. As a result, they can be used either to clean-up the phase space of the accelerator beam or reduce it drastically for tune-up purposes. Table I illustrates this for several possible foil combinations -- all of which are commercially available.

To insure that the effective angular divergence depends only on the size of the second collimator, the output divergence at that point should not depend on the input divergence at the first collimator, i.e., the first order transformation element $R_{22} \equiv 0$. Under this constraint, particles diverging from the axis of the first collimator will be parallel to the axis at the second and displaced from it. Similarly, in order that the beam size at the second collimator be independent of the size at the first, $R_{11} \equiv 0$.

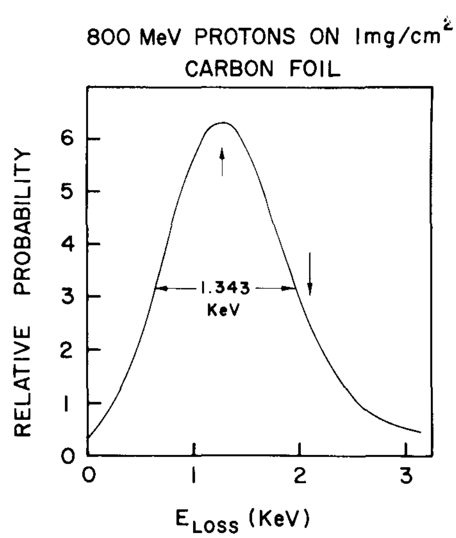

Fig. 2. Energy loss straggling of 800 MeV protons passing through a charge-stripping foil. The arrows indicate a most probable energy loss of 1.27 keV and a mean energy loss of 2.10 keV. Note that $(\delta T/T) = \pm\ 0.40\%$ or more than $\pm$ 3 MeV for 800 MeV. The calculation is based on Ref. 4.

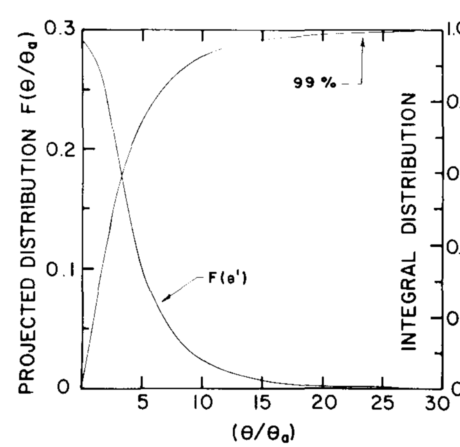

Fig. 3. The projected angular distribution and its integral as a function of reduced angle, θ/θ_a, for a mean number of collisions of 10.7. The angle, θ_a, is the screening angle which, for 800 MeV protons, is 5.6 x 10^{-6} radians. The calculations are discussed further in Section V and in Ref. 5.

TABLE I

ε_x and ε_y are the effective transverse emittances at the exit of the accelerator for various combinations of strippers. $\underline{\delta x}^{in}$ defines the effective phase ellipse after anti-stripper #1 and $\underline{\delta x}^{out}$ the corresponding quantity incident on stripper #4, the object of Beam Line C. The notation is the same as for a type 1.0 entry code in TRANSPORT. The output ellipse, $\underline{\delta x}^{out}$, was computed to second order with TRANSPORT. The last column gives the approximate factor by which the H^- current incident on stripper #4 should be reduced.

Anti-Stripper	ε_x (cm-mr)	ε_y (cm-mr)	$\underline{\delta x}^{in}$ (cm,mr,cm,mr,%)	$\underline{\delta x}^{out}$ (cm,mr,cm,mr,%)	Reduction Factor
none	1.0	1.0	(1.099,0.927,1.231,0.951,0.260)	(0.674,1.519,1.099,0.936,0.260)	0.999
none	0.1	0.1	(0.347,0.293,0.389,0.301,0.260)	(0.213,0.480,0.348,0.296,0.260)	0.960
(2)*	6.8×10^{-3}	1.1×10^{-2}	(0.340,0.020,0.337,0.030,0.260)	(0.186,0.149,0.143,0.268,0.260)	2×10^{-2}
(1)*	1.5×10^{-3}	1.3×10^{-3}	(0.005,0.287,0.005,0.261,0.260)	(0.140,0.420,0.342,0.035,0.260)	5×10^{-4}
(1),(2)*	1.0×10^{-4}	1.6×10^{-4}	(0.005,0.020,0.005,0.033,0.260)	(0.011,0.034,0.043,0.006,0.260)	2×10^{-5}
(1),(2),(3)**	1.0×10^{-4}	1.6×10^{-4}	(0.005,0.020,0.005,0.033,0.260)	(0.010,0.030,0.043,0.005,.0012)	3×10^{-7}
(1),(2)†	6.4×10^{-6}	1.0×10^{-5}	(.00125,.005,.00125,.008,0.260)	(.0044,.018,.0108,.0015,0.260)	7×10^{-8}
(1),(2),(3)††	6.4×10^{-6}	1.0×10^{-5}	(.00125,.005,.00125,.008,0.260)	(.0025,.007,.0108,.0013,.0003)	3×10^{-10}

* The anti-strippers used at stations #1 and #2 consist of a 4-mil hole in a 1 mg/cm^2 carbon foil.

** Same as above except that station #3 is assumed to have a 2-mil-wide line in the y direction.

† The anti-strippers used at stations #1 and #2 consist of a 1-mil hole in a 1 mg/cm^2 carbon foil.

†† Same as above except that station #3 is assumed to have a 1/2-mil-wide line in the y direction.

Then, trajectories parallel to the axis at the first collimator will crossover at the second and the transformation between the two will be

$$R = \begin{pmatrix} 0 & f \\ -1/f & 0 \end{pmatrix} .$$

In order to treat both transverse directions symmetrically we have used a triplet so that both x and y crossovers occur at the same point. The radius, r, of the second collimator which is required for a given effective angular divergence is then

$$r_2 = R_{12}\,\theta_1^{max} \rightarrow \theta_1^{max} = r_2/f.$$

Similarly,

$$x_1^{max} = y_1^{max} = r_1.$$

This same idea can also be used to determine the angular divergence of the beam in which case the second collimator would be replaced with a detector, i.e., at the focal length of the lens.

The theoretically best attainable resolution in the switchyard depends on the minimum slit width obtainable at the location of the third anti-stripper. For a 1/2-mil-wide slit in a 1 mg/cm^2 carbon foil the momentum resolution of the beam incident on the stripper will be 6×10^{-6} full width at the base. For the phase space created by the first two anti-strippers there is a monochromatic waist located about midway between the last quad triplet (the achromatizer) in Line X and the last two bending magnets. Since the dispersion, D, is a linear function of path length in this region and the system is achromatic, the location of the point where the resolution is best must occur somewhere short of the waist. One can find that point knowing the R and σ matrices at the waist in the dispersion plane. Using TRANSPORT[6] notation, it is easy to show that the resolution a distance, ℓ, from the waist as measured at the base of the spatial distribution, is

$$\frac{\delta p}{p} = R(\ell) = 2\,\frac{\sigma_{11}(\ell)}{D(\ell)} = 2\,\frac{[\sigma_{11}(0) + \ell^2\sigma_{22}(0)]^{1/2}}{R_{16}(0) + \ell\, R_{26}(0)} .$$

Minimizing this quantity with respect to ℓ then gives:

$$\ell_m = \left.\frac{R_{26}}{R_{16}}\right|_o \times \left.\frac{\sigma_{11}}{\sigma_{22}}\right|_o .$$

Inserting the numbers for our particular case shows that an adequate resolution, as measured at the base of the particle distribution, of $R(\ell_m) = 6 \times 10^{-6}$ is possible using a 0.0005 in. slit.

V. DETERMINATION OF BEAM ENERGY AND BEAM CURRENT

Since the existence of a proton beam in experimental Area C is predicated on stripping some fraction of the incident H^- beam, one always has available a source of electrons whenever there is proton current in this line. This electron current has a number of uses. From the experimenters viewpoint, however, these electrons are probably best used to measure the beam current and beam energy, since these may often be required to an accuracy which is difficult to obtain in practice, particularly at the energies and beam intensities which will be used at LAMPF. Thus, although there are a number of possibilities, our main concern was with these two functions. Our initial goal was to achieve absolute measurements of the transmitted proton current to within one part in 10^3 and the proton momentum to within one part in 10^4.

Since we were interested in making absolute measurements, it seemed advisable to consider a 180° spectrometer system. The accuracy of the energy determination depends primarily on the resulting angular divergence and momentum spread of the stripped electrons, since the size of the incident H^- beam is relatively small. The momentum spread depends primarily on the energy loss in the foil but not on the fermi motion in the H^- atom. Assuming a dE/dx of 2 MeV/gm/cm^2, the fractional energy loss will be less than the spread in the incident H^- beam, so that the emerging electrons will have a relatively well-defined energy with the contributions from chromatic aberrations being small but depending on the particular choice of spectrometer. Some representative electron energies of interest for LAMPF are:

	P(MeV/c)	E_e(keV)	P_e(keV/c)	$\beta_{e,p}$
E_p = 800	1463	436	797	0.842
500	1090	272	594	0.758
200	644	109	351	0.566

The accuracy of the beam current determination depends on a number of things, such as the background flux of electrons resulting from losing protons in the beam plumbing along the line, residual gas stripping and the like. However, the single most important factor is the difficulty of actually collecting the stripped electrons. Again the primary problem appears to be that of angular divergence -- due to plural scattering in the stripping foil.

The mean number of single collisions, n, in a foil depends only on the β of the particle so that it is essentially the same for both protons and electrons. According to Moliere, this is given by

$$\log n = 8.215 + \log\left[\frac{t}{AZ^{1/3}}\left(\frac{\gamma^2}{1.13 + 3.76\gamma^2}\right)\right]$$

where t is the thickness in g/cm^2 and γ is $\alpha Zz/\beta$. For $\beta = 0.842$, the mean number of collisions is 10.7 which means we are in the region of plural scattering which, so far, has not been described analytically as Moliere and others have done for $n \gtrsim 20$. The results shown in Fig. 3 were therefore determined numerically and should be applicable for both protons and electrons -- the only difference being in the atomic screening angle, θ_a, which is

$$\theta_a = \frac{1.14\alpha Z^{1/3}}{(p.m_e c)}\,[1.13 + 3.76\,\gamma^2]^{1/2} \quad \text{[radians]}$$

where p is the momentum of the incident particle. For the case of interest here the ratio of the scaling factors, θ_a, goes essentially as m_p/m_e = 1836. Thus, while the "multiple" scattering of the proton beam in the foil is insignificant, the same is not true for the electrons. For electrons, $\theta_a \approx 10$ mr, so that in order to collect more than 99% of the beam one would need an acceptance half angle of $\theta \approx \pm 240$ mr or almost 14° in both directions.

Figure 4 shows a possibility[7] that we are trying to adapt for this purpose. The thing which

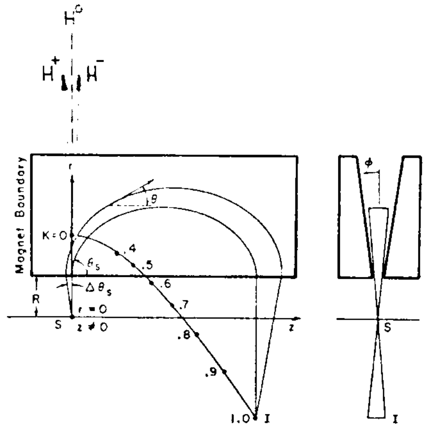

Fig. 4. General layout of 180^{o} double focusing spectrometer.

makes this an attractive possibility is that it is not a conventional n = 1/2 magnet, so that only technical limitations limit its acceptance angle in the ϕ direction to something less than 90^{o}. On the other hand, if one considers the conventional 180^{o} homogeneous field magnet, it can be shown that its higher order geometric aberrations in θ can be eliminated by field shaping, so that a combination of these two approaches should yield a significantly better instrument. Of course, it is not necessary to combine both current and energy functions in the same instrument, but this has many attractive advantages, since then both types of information are simultaneously and continuously available for feedback purposes. If this is not done, there are a number of simpler approaches which are possible but these will be discussed elsewhere in a more complete report on this problem.

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