THE BEAM TRANSPORT DESIGN FOR THE LAMPF INJECTOR*

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Introduction

The injector area for LAMPF has been designed to handle three ion sources. There are two high-intensity 50-mA sources, one possibly adaptable for H^- acceleration, and a polarized ion source, all for 750-kV protons. This proliferation requires a more elaborate beam transport[1] than has been used before. The basic features for this system have been determined from the Kapchinskij-Validimirskij[2] equations for beam dynamics with space charge, emittance, and linear lenses, and from investigations of the aberrations induced by the beam transport magnets. The problems of phase-space matching and beam depolarization have also been considered.

Design Criteria

The design of the LAMPF beam transport system has been chosen so that

1) Ion sources have convenient spacing.
2) The two high intensity sources feed similar systems.
3) The polarized ion beam transport system has no bends.
4) A minimum of effective emittance is induced by lens aberrations.
5) Momentum dispersion of the bending magnets is zero.

Lens Aberrations - General

In estimating the effective emittance increase due to lens aberrations a simple criterion was used. If a beam of zero emittance passes through a lens its phase-space plot might be warped as shown in Fig. 1. The effective emittance is the area of an ellipse required to enclose it, approximated by a rectangle. This effective emittance is

$$E/\pi \cong \frac{4X_o^2}{\pi}\,\frac{\Delta d}{d^2}$$

where X_o is the beam radius, d is the distance to the focus, and Δd is the spread in d due to aberrations.

All aberration calculations for lenses assumed perfect manufacture with simulated fields satisfying Maxwell's equation to third order. A standard case was taken for which a drifting beam of zero current and emittance would have had a 1.4-cm radius at the center of the lens, and the focus-to-focus distance was 3.2 m. The beam profile and the fields in the lenses were very close to those obtained from the first order space-charge design.

Lens Aberrations-Spherical Lenses

The spherical magnetic and electric lenses[3] have considerable appeal. They have been thoroughly studied by electron microscopists; the theory is well developed, and their construction and operation are simple. For a magnetic solenoid of given focal length and thickness it has been shown that the on-axis field for minimum spherical aberration is

$$B_z = B_o e^{-\alpha z^2}.$$

This is closely approximated by a small gap to diameter ratio iron-shielded lens. Using the spherical aberration coefficient for this lens with the emittance formula we get

$$\frac{E}{\pi} = \frac{1.72\, r_o^4}{D^2 f} = \frac{52\ \text{cm-mrad}}{D^2\,\text{cm}}$$

where f is the focal length and D is the diameter of the lens. This is large compared with our goal of $E/\pi = 1$ cm-mrad beam emittance from the ion source. The optimum Einzel lens is about a factor of 10 worse, although it could be ruled out by voltage limitations anyway.

Lens Aberrations-Quadrupole Lenses

An optimum design for quadrupoles is not known, thus we chose to make numerical studies with several reasonable designs. In the equations of motion to third order the relevant fields are

$$B_x = yg\left(1 - \frac{g''}{12g}\,(3x^2 + y^2)\ \ldots\right)$$
$$B_y = xg\left(1 - \frac{g''}{12g}\,(3y^2 + x^2)\ \ldots\right)$$
$$B_z = xyg'$$

A hand calculation will show that a trapezoidal approximation (Fig. 2) to the on-axis gradient is sufficient for accurate third-order transformation coefficients; in fact a zero-length fringe field would not have significantly changed our results. A calculation for one case of a smooth gradient variation verified these conclusions.

Three triplet designs of overall length from 0.6 to 1.2 m were studied, all with 5-cm fringe field lengths:

1) Short 5/10/5 cm effective pole lengths
2) Medium 10/20/10 cm effective pole lengths
3) Long 20/40/20 cm effective pole lengths

Transformation coefficients to third order were obtained, and final phase-space plots were made for particles chosen at random from point sources of ±9 mrad divergence in both planes, which made the beam profile in the lens closely resemble the space-charge beam. Typical phase-space plots are shown in Figs. 3a and 3b. Table I summarizes the calculations. Since the aberrations were larger in the DFD than in the FDF planes, it was thought that a quintuplet might be more equal in its treatment of the X and Y planes. This was the case, but aberrations in both planes were larger. The conclusion is that our long, widely spaced quadrupole triplets should be an order of magnitude better than the solenoid.

Table I

Effective Area Divided by Pi of Phase Plots

Length	Long (20/40/20)	Medium (10/20/10)	Short (5/10/5)
1.2	.045 + .079	.055 + .115	.075 + .181
1.0	.080 + .121	.086 + .156	.120 + .217
0.8	-	.137 + .212	.183 + .272
0.6	-	.272 + .331	.321 + .445

Radial and Vertical Emittance in cm-mrad

Lens Aberrations-Bending Magnet

The spatial aberrations of a bending magnet are of second order, and the SLAC program TRANSPORT[4] was used. Since the beam is at a double waist at the bending magnet entrance, the effective emittance increase is small, about 0.1 cm-mrad.

With the 1-m medium triplets and the two bending magnets, the sum of the emittance increases for the transport system is slightly less than 1 cm-mrad.

Space Charge Considerations

For our expected beam quality the expansion is due mostly to space charge. For a uniform charge density the beam radius is

$$r = r_o\left[1 + \left(\frac{Z}{r_o}\right)^2 \frac{ei}{4\pi\epsilon_o MV^3} + \dots\right]$$

where r_o is the beam size at the waist. If R is the beam radius at a distance L from the waist, then

$$r_o \simeq \frac{R \pm \sqrt{R^2 - 4L^2 ei/4\pi\epsilon_o MV^3}}{2}$$

Hence, given a lens radius R there is a maximum drift distance

$$L \simeq R\sqrt{\frac{\pi\epsilon_o MV^3}{ei}}$$

and an optimum waist size $r_o = R/2$. In this way the transport system has only one parameter - either the lens radius or the beam waist. For our design of 50 mA at 750 keV, $r_o = 0.7$ cm, thus R = 1.4 cm and L = 160 cm.

Transport System

The transport layout is shown in Fig. 4. Basic dimensions were derived from consideration of the best use of building space and from the requirement of a nondispersive system, assuming that no serious problems would arise with the transport optics. Dispersion is eliminated by the lens, a quad triplet, between the two 45° magnets. Two triplets, operating at unity magnification, are to be used to transport the polarized ion beam to the double 45° bending magnet. A spin precessor (Wein filter) will be located at the crossover between the two triplets. Ray tracing calculations for representative particles in the 750-keV polarized proton beam indicate that the maximum depolarization of any particle is 0.1% so that depolarization effects in the beam transport system are negligible.

The ion-source lens may be a quadrupole quadruplet. The calculated beam profiles for this matching system are shown in Fig. 5. Another method for effecting the same matching using a nonsymmetric triplet is shown in the Fig. 6. In order to match four quantities - radial and vertical size and divergence of the incoming beam - to the linac four variables are needed to cover all possibilities. In practice the spacing will be arranged so that for the expected ion source and transport operation only two will be used. Small deviations in current, emittance, magnet operation can then be corrected with the other two quads. It might be noted that the beam transport code can adjust four quad parameters to achieve arbitrary beams. Using an analog more sophisticated than would be used by an operator and using an idealized beam, divergence of the searches was more common than convergence, thus there may be some difficulty in using a quadruplet in practice. Tests will be made at 200 kV on a quadruplet measuring before/after emittance and phase space. The lens at the column exit will be operated at nonunity magnification since the ion source beam is small, 0.5-cm radius, at its effective source, and the transport system is more amenable to a 0.7-cm radius beam.

Stability Considerations

A computer code based on the Kapchinskij-Vladimirskij[2] equations for beam transport was used to calculate gradients and test the system for stability with respect to changes in beam current, quad currents, and emittance. About 90% of the beam lay in the correct final phase space for ±10% change in beam current, or for 0.3% random quadrupole current variation. Quad gradients are around 150 G/cm for the 1 m medium triplets.

References

1. A more detailed analysis of the transport optics is contained in an internal report, "Transport System Optics," MP-4/PWA-1, July 1967.
2. I. M. Kapchinskij and V. V. Vladimirskij, Conference on High Energy Accelerators and Instrumentation, Session 3, 274, CERN, Geneva, 1959.
3. Electron Optics and the Electron Microscope, V. Z. Zworykin & Co., Ch. 17. This summarizes theoretical investigations of several magnetic and electric spherical lenses.
4. C. H. Moore, S. K. Howry, and H. S. Butler, TRANSPORT. SLAC

*Work performed under the auspices of the U. S. Atomic Energy Commission.

DISCUSSION

(P. Allison)

REGENSTREIF, UNIV. DE RENNES: I was wondering if you had seen the paper presented to the Los Alamos conference by Tanguy and myself, in cooperation with Faure from Saclay, in which we made a calculation of the aberrations in both planes of a triplet. The results you have shown seem to be quite similar to those we obtained two years ago, except that we have worked in the real phase space. It is not too clear to me what you define by your expression for emittance, if you are using zero emittance. I would also like to draw your attention to a paper that has come out a few months ago, on the theory of a quadruplet which gives you an optimizing procedure for the quadruplet characteristics. Finally, at CERN we have been doing some work in connection with an rf separator for the Serpukhov accelerator; there we have established analytical conditions for maximum angular acceptance, and minimum chromatic aberrations.

LEISS, NBS: Is your deflection system achromatic?

ALLISON, LASL: Yes, the first order calculations used the Kapchinski-Vladimirski equations and emittance plays a small role in expanding the beam compared with the space charge, if we get what we want out of the ion source.

LEISS, NBS: So the space charge does not add dispersive effects?

ALLISON, LASL: Well, the system is nondispersive. No.

BENJAMIN, BNL: Have you looked into the aberrations due to the crossed field device which you are using as a spin precessor? I noticed that you did focus the beam, making it cross over within the device, which should help. However, the focal length of the device should be long compared to the length of the device in order for the crossing technique to effectively cancel the aberations. In addition to the characteristic cylindrical lens effect, you have lens effects at the entrance and exit of the device due to magnetic and electric fringing fields.

ALLISON, LASL: That's right. That has been investigated for just the reasons you mentioned -- that is why the focus is inside the spin precessor.

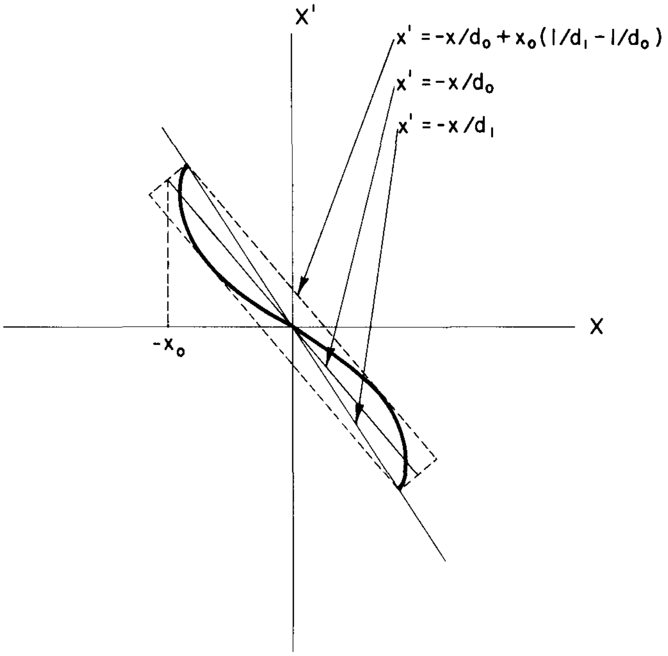

Fig. 1. Beam phase space after a bad lens.

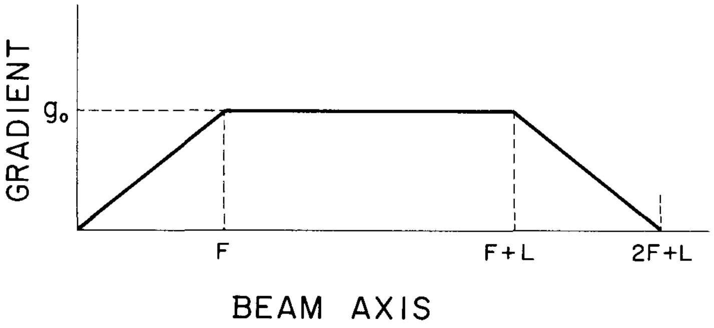

Fig. 2. On-axis quad gradient.

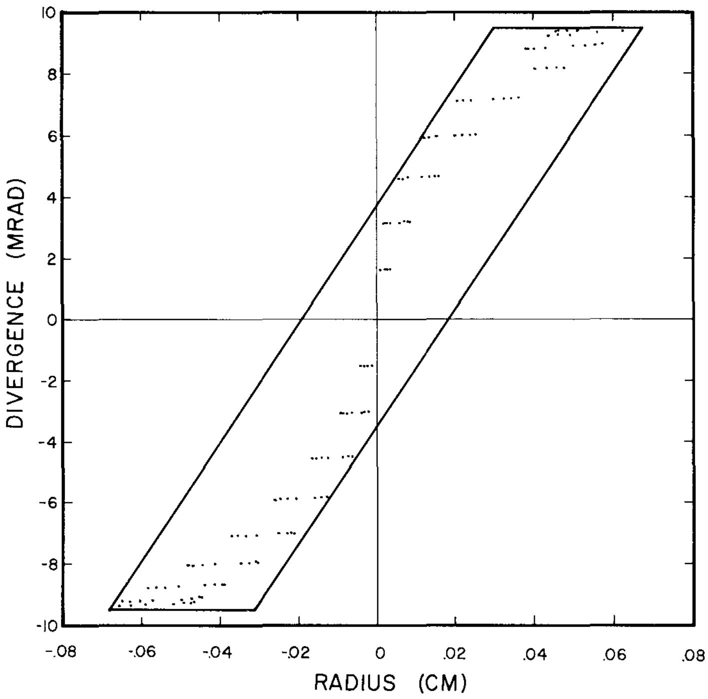

Fig.3a. Phase space distortion produced by short, 1-m triplet in the DFD plane.

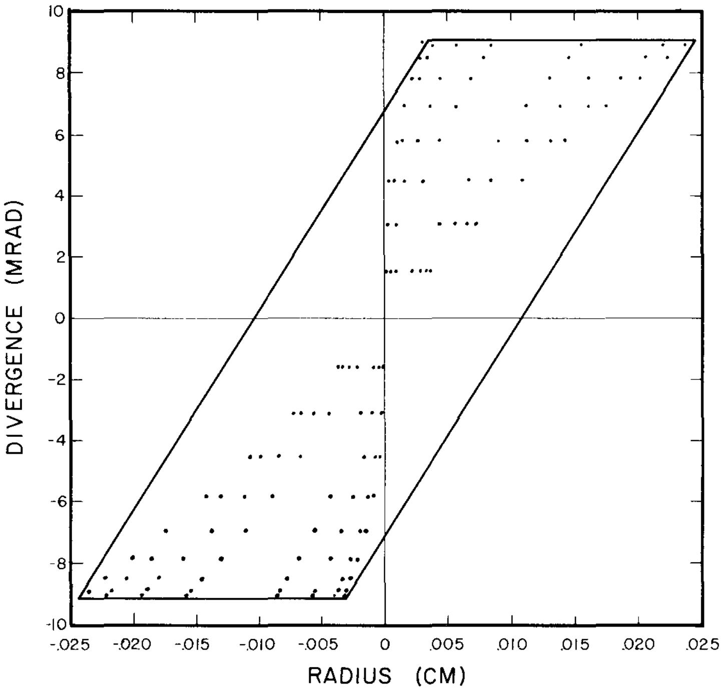

Fig.3b. Phase space distortion produced by short, 1-m triplet in the FDF plane.

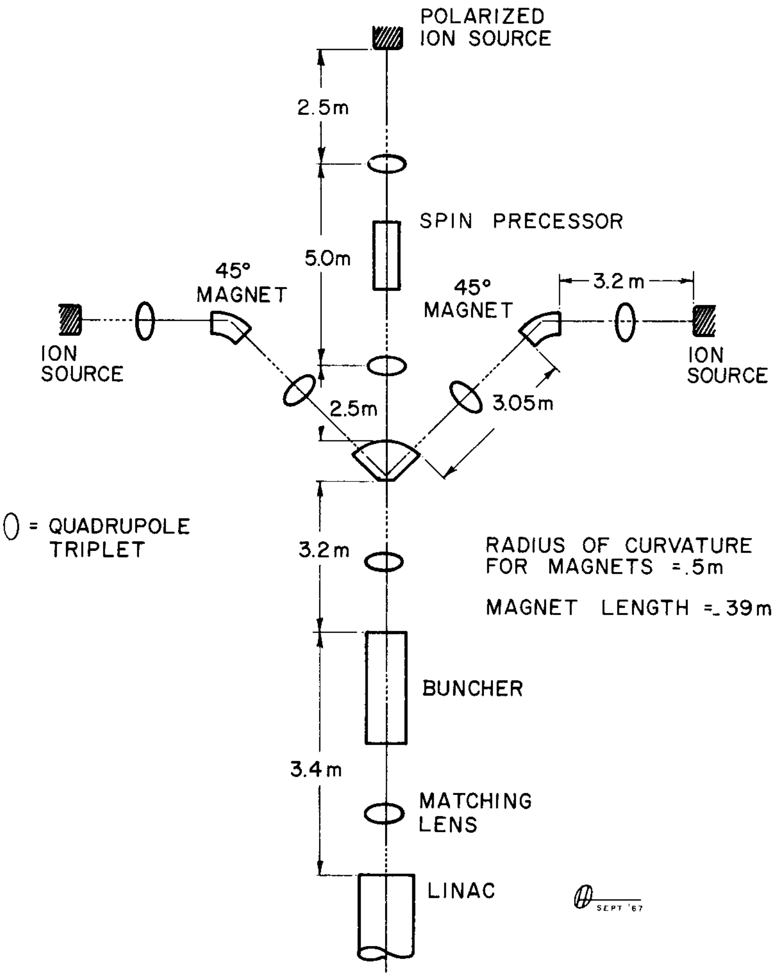

Fig. 4. Beam transport layout.

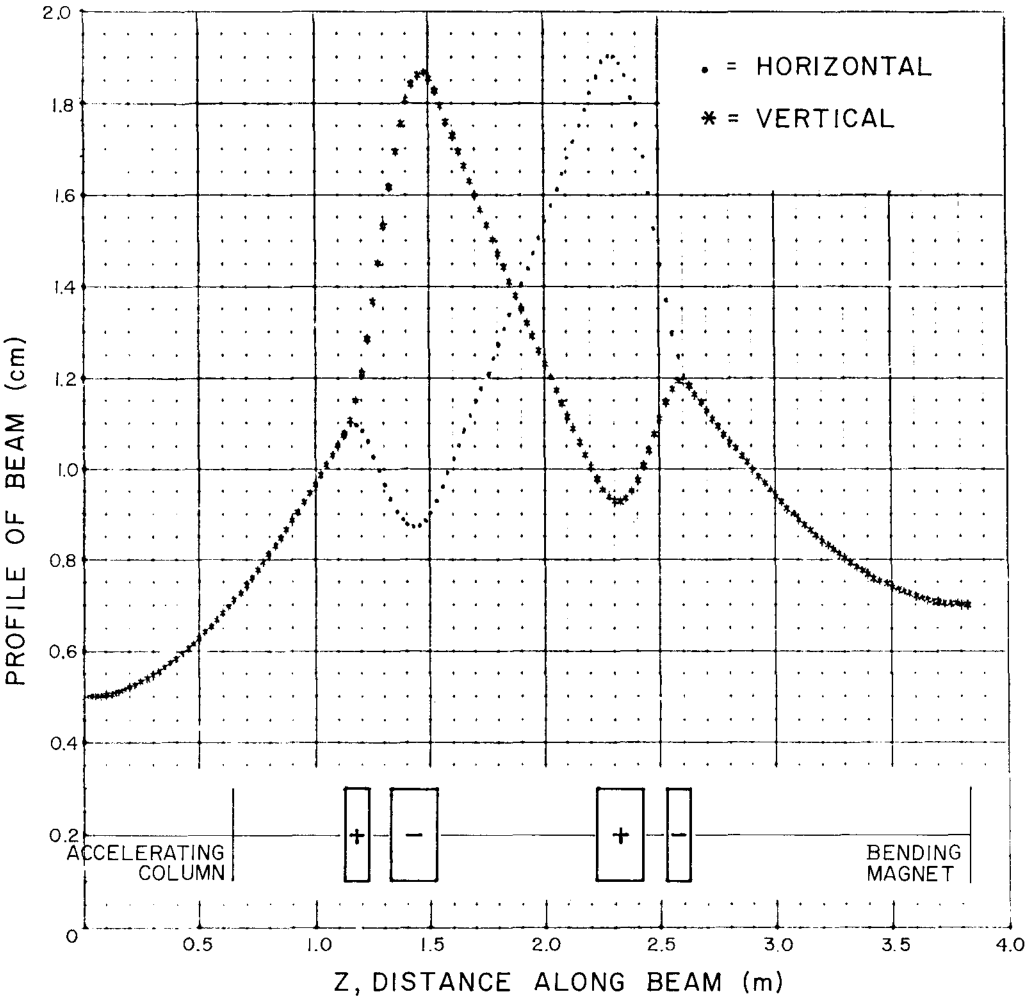

Fig. 5. Quadruplet ion-source lens.

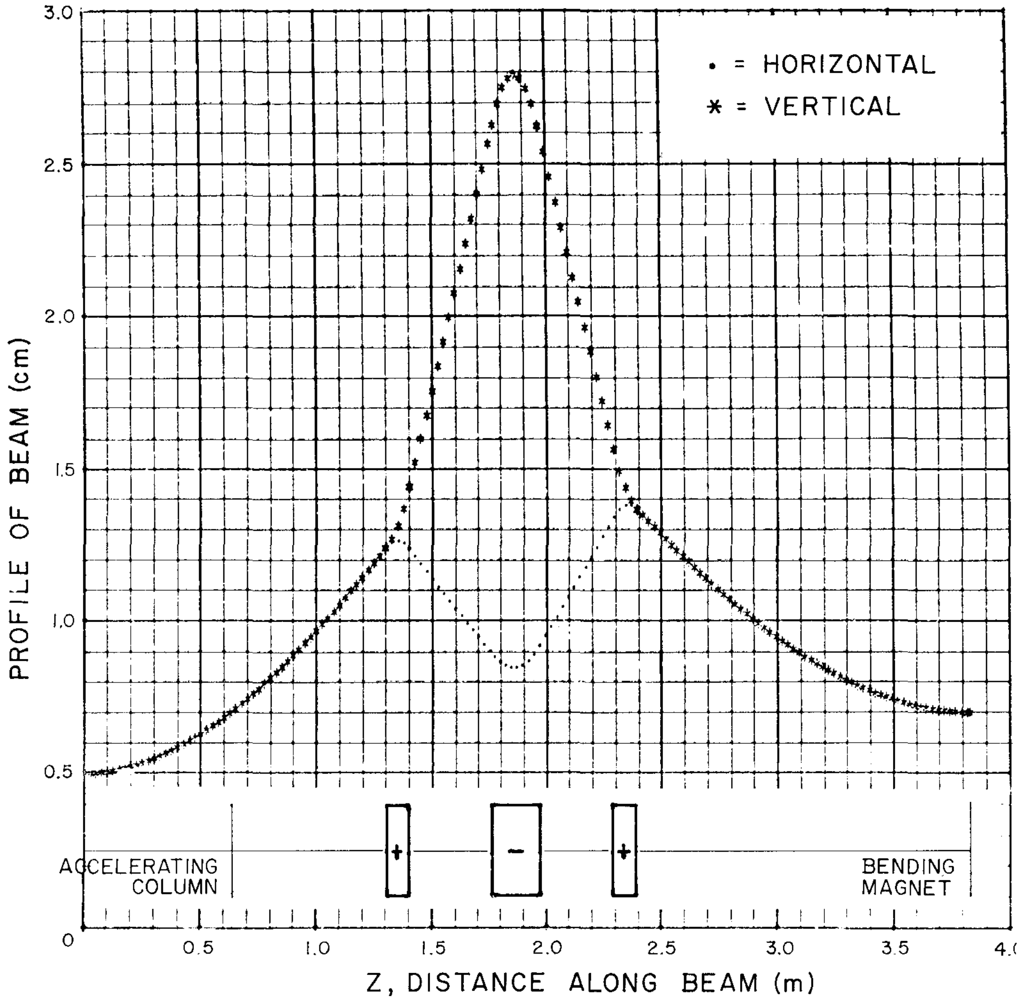

Fig. 6. Nonsymmetric triplet ion-source lens.