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by

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ABSTRACT

After describing the transition region between the LAMPF drift-tube linac and side-coupled linac, we discuss the function of the region, its present shortcomings, and the need for a redesign. Then we present the new design, its advantages, and its expected performance. Included are detailed results of beam-dynamics studies giving the ranges of input- and output-beam shapes that can be successfully matched in the new transition region. To improve the present operation of the two linacs, we suggest small changes that will allow us to easily match the beam between the two linacs. Finally we describe the methods used in our beam-dynamic studies so that effects of future improvements to the new design can be examined.

I. INTRODUCTION

The beam transport section between the 201.25-MHz linac or drift-tube (DT) linac and the 805-MHz linac or side-coupled (SC) linac at LAMPF has been named the transition region (TR). Its two main functions are 1) to transversely match the output H^+ and H^- beams from the 201.25-MHz linac to the acceptance of the 805-MHz linac, and 2) to increase the flight path of one beam by 7.98 cm compared with the other beam so that both beams arrive at the 805-MHz linac at the proper longitudinal phase for capture and acceleration. The 7.98 cm is the distance traveled by a beam particle in one-half of an 805-MHz rf cycle.

The present TR now has a host of operational problems. Furthermore, when the new proton storage ring (PSR) becomes operational, H^+ production running would be seriously curtailed using the present TR, because it will not allow the simultaneous production of both a high-current H^- beam for the PSR and a high-current H^+ beam for normal production.

In this report we discuss the problems of the present TR in detail in Sec. II, and in Sec. III we present a new design of the TR and discuss its advantages and improvements. Section IV describes the methods for finding transverse matches for the various sections of the new TR and the ranges of input and output parameter space where acceptable matches can be found. We explain the greatly simplified method of adjusting the longitudinal phases of the H^+ and H^- beam in Sec. V, present steering magnet studies in Sec. VI, and discuss the effects of the TR design modifications that were made after our detailed beam-dynamic studies in Sec. VII.

II. DISCUSSION OF THE PRESENT TR

Beam-particle dynamic studies show that, if we wish to operate a linac with low emittance growth, low spill, and maximum transmission, then we should match the input beam distribution, for example, beam emittance to the acceptance of the linac. The acceptance is usually assumed to be ellipsoidal in six-dimensional space. In practice, because this six-dimensional matching problem is very complicated, the assumption is usually made that successful operation can be obtained by matching the beam to the three two-dimensional projections of this six-dimensional space. These two-dimensional projections, the x - x' projection, the y - y' projection, and the W - ϕ projection are again assumed to be ellipsoidal. The variables x and y are the transverse horizontal- and vertical-position coordinates, x' and y' are the ratios of the corresponding transverse components of the velocity to the axial velocity, and W and ϕ are the longitudinal energy and phase components of the particles. The equation most often used to describe the ellipse is

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = E/\pi ,$$

where

$$\beta\gamma - \alpha^2 = 1$$

and where E is the area of the ellipse called the emittance of the beam. The variables γ , β , and α are called ellipse parameters. It can be shown¹ that the maximum values of x and x' are given by

$$x_{\max} = \sqrt{\beta E / \pi}$$

and

$$x'_{\max} = \sqrt{\gamma E / \pi} .$$

A plot of $x_{\max}$ vs position along the linac or beam-transport line is said to show the "envelope" of the beam.

If an ideal beam were matched to an ideal linac and measured at homologous points in a transverse periodic structure, we would observe an elliptical distribution characterized by ellipse parameters. These parameters would be periodic and would depend on where the measurements are made in the periodic structure. They would also have a very slow dependence on the energy of the synchronous particle. SIMALAC-code studies have predicted ellipse parameters of the transverse acceptance of the SC linac. In principle, the transverse matching of the beam from the DT linac to the SC-linac acceptance can be accomplished by measuring the beam emittance, fitting the beam distribution to an ellipse, and using codes such as TRACE² or TRANSPORT³ to find settings for the TR quadrupoles that will transform the beam shape to that of SC-linac acceptance. Although matching is obtained by adjusting four quadrupoles to obtain four shape parameters, for example, the values of the α 's and β 's, the equations involved are nonlinear and coupled. Analytic solutions to these equations have yet to be found; the usual method of finding quadrupole solutions is to use iterative fitting codes such as TRACE or TRANSPORT. In practice, the matching procedure for our two-beam operation is very complicated in the present TR, and it is virtually impossible to match both the H^+ and H^- in both linacs.

We have been operating with the TR design shown in Fig. 1. The H^+ and the H^- beams are separated in the bending magnet BM01. The H^+ beam is displaced using 4° bends and recombined with the H^- beam in BM04. The H^+ section is called the "main line." The H^- side or "side track" has larger bends and is used to increase or decrease the flight path of the H^- beam. Because there are no quadrupoles in the side track, we can only use the quadrupole doublets QD03 and QD04 for matching the H^- beam to the SC linac. The matching of the higher intensity H^+ beam is coupled to the H^- matching solution because the H^+ also traverses the QD03 and QD04 quadrupoles. When we include these quadrupole settings in the matching of the H^+ beam, we find that the required quadrupoles QD01 and QD02 have large gradients and produce large, unacceptable H^+ beam-envelope oscillations. Therefore, we must adjust the quadrupoles QD03 and QD04 so that the H^+ has an acceptable behavior in the whole TR. The adjustment of these quadrupoles changes the required shape of the H^- beam at the exit of the DT linac; this shape can only be obtained by deliberately mismatching the H^- beam in the DT linac. Because the H^- is mismatched, its shape is both degraded and made very sensitive to the longitudinal tuning of the DT linac. The final H^- tune is therefore a compromise that is found in a very time-consuming iterative process.

The longitudinal matching is very rudimentary because we have no equipment capable of measuring the two-dimensional longitudinal emittance. Fortunately, empirical results indicate that the matched longitudinal ellipse should be upright and narrow in phase. These criteria simplify the longitudinal tuning to adjusting the relative phase between the rf oscillators of the two linacs, so that the average phase of the beam distribution is the

Fig. 1.
The original TR.

synchronous phase of the SC linac and the phase width (adjustable by varying the phase and amplitude of the radio frequency in the DT linac) is a minimum.

Again, our two-beam operation and the design of the present TR make the longitudinal-phase adjustment of the two beams coupled and complicated. Many bending magnets in a side track are involved in changing the H^- beam flight path, and as a result these bending magnets are typically set up only once for a run cycle. During production running, beam-spill difficulties that often occur along the SC linac are usually eliminated by adjusting the relative phase between the rf fields in the two linacs. This adjustment also changes the H^- phase or time of arrival at the SC linac and can affect the energy distribution of the H^- beam at 800 MeV. To offset this change by adjusting the H^- flight path in a side track is impractical during production running. Furthermore, when large corrective attempts were made, the aperture of the TR proved to be too small for the required path-length changes.

The lack of independent H^+ and H^- transverse matching capability, the difficulty in making H^- longitudinal phase adjustment, the small apertures, the beam-steering problems caused by two closely spaced steering magnets, and the inability to handle H^- beams beyond 5 μA have caused us to redesign the TR. The proposed new TR will, in addition to removing the above difficulties, contain more beam-diagnostic equipment and space for a bucket rotator capable of longitudinally matching beam. The bucket rotator would act as a lens in longitudinal phase space.

III. THE NEW TR

We have designed a new TR with the aim of eliminating the current shortcomings of the present TR. Figure 2 shows the design of the new TR.

Fig. 2.
The final design of the new proposed TR.

Because the beam elements in the new TR must fit between the existing LAMPF linacs, we had a limit on the maximum number of elements and had few options as to the placement of these elements. As a result, some novel configurations, which would greatly simplify matching, are not possible. We gained additional space by making the bending angles in the new TR as large as possible, but not so large as to cause the stripping of H^- beam in the bending-magnet fields. We chose 20° bends using 11.87-kG fields. The fraction f of H^- ions that are stripped is given by

$$f = 1 - e^{-L/\gamma\beta cT} ,$$

where L is the path length in the field, γ and β are the usual relativistic parameters, c is the speed of light, T is the lifetime

$$T = (A/3 \times 10^7 \beta \gamma B) \times e^{D/3 \times 10^7 \beta \gamma B} ,$$

and where B is the magnetic field in kilogauss and A and D (Ref. 4) are given by

$$A = 7.96 \times 10^{-6} \text{ V/m}$$

$$D = 4.256 \times 10^9 .$$

Using these parameters, we find that $f = 7 \times 10^{-7}$ for our 20° bending magnets. A more recent measurement⁵ of these parameters predicts that $f = 6 \times 10^{-7}$. Both of these values are sufficiently small to be acceptable.

The new TR will have three beam lines instead of two as in the present TR. These lines have been called (from top to bottom in Fig. 2) the short track, the straight-through section, and the long track. In each line we have placed four quadrupole magnets so that independent matching of the ellipse parameters can be made in each line. The quadrupole placement in each line was chosen to give the maximum ranges of input- and output-beam shapes for which acceptable matching could be found.

During normal operation, the 20° bending magnet BM01 will separate the H^+ and the H^- beam, and the 20° bending magnet BM04 will recombine the beams. In the short track, 20° bends will occur in BM02 and BM03; the beam path will not change in this line. The path length in the long track will be varied to adjust the relative phase between the two beams as they arrive at the SC linac. This variation will be accomplished by varying the fields or bending angles in the bending magnets BM05-BM08. The combined bends in each of these two pairs of magnets BM05, BM06 and BM07, BM08 will always be 20° . One power supply will provide current in series to all the windings in the magnets BM01-BM04, as well as current for half the windings in each of the magnets BM05-BM08. A second power supply will provide current in series to the other halves of the windings in magnets BM05-BM08. The resulting fields from these two currents will be opposing in magnets BM05 and BM08 and will add in magnets BM06 and BM07. This arrangement has two significant advantages. First, for small drifts or changes in the two power supplies, the angles and positions of the output beams at the SC linac will be unaffected. Second, the phase or flight path of the beam in the long track can be adjusted with just one knob controlling the output current of the second power supply; no additional steering or quadrupole changes should be necessary. This arrangement will greatly simplify the relative phasing of the beams into the SC linac, will allow phase adjustments to be made in both beams during production running, and should result in a more constant and desirable H^- beam energy distribution at 800 MeV. Note that, if the absolute phase of the beam is incorrect for only the beam in the short track, the relative phase is also incorrect. The procedure to correct such a problem will involve adjusting the rf phasing between the two linacs to correct the beam phase in the short track and a readjustment of the path length in the long track to correct the relative phase.

All the bending magnets will be of the same design and will have rectangular pole pieces. As a result, these magnets will be interchangeable and will cost less to design and fabricate.

We have increased the clear aperture of the new TR from 3.0 to 4.9 cm. This increase will reduce the spill levels in the TR, will allow greater flexibility in matching present and future beams into the SC linac, and will give greater freedom in steering the beams.

We have introduced a large amount of additional beam-diagnostic equipment that will be contained in the beam boxes labeled BB. Standard slit and collector emittance stations have been positioned at the exit of the DT linac and at the entrance to the SC linac. These stations will have increased resolution, which is badly needed for our present high-brightness beams, and will be invaluable in verifying solutions from our matching codes. Numerous beam-position monitors will be installed to assist us in steering the beam.

The straight-through section contains portions of the emittance gear mentioned above. It can function as an emergency line if we lose the bending magnets; obviously only one beam could then be accelerated in the linac. The beam dynamics of this line should be well understood because of its relatively simple design and, therefore, will be useful in beam-dynamics studies in and around this part of LAMPF.

Carbon absorbers will be installed at the entrance of both the long and short tracks. These absorbers are positioned to intercept any low-energy beam that could result from the failure of any of the tanks in the DT linac. In the event that such a failure occurs, these absorbers will protect the beam pipe from being ruptured by the beam. Such occurrences, although highly unlikely because of numerous interlocks, have happened.

We have also provided space for a bucket rotator. The procedure for using such a device would be to adjust the amplitude and phase of the radio frequency in the DT linac until the phase projection of the longitudinal emittance is minimized at the SC linac for the beam that traverses the long track. The bucket rotator would then be activated to obtain the same narrow phase projection for the beam in the short track.

To examine the ranges of input- and output-emittance spaces that the new TR can match, we have assumed that both the expected high-current H^+ and H^- beams would need to be matched in both linacs. We have also assumed that the ellipse parameters characterizing the x and y transverse-emittance space of the matched H^+ are those of the y and x transverse-emittance spaces of the matched H^- beam; that is, we have simply interchanged the x and y planes for the H^- case. This last assumption, although reasonable, requires experimental proof. In the past most of our matching studies have been done using the H^+ beam. In this study we have used the input ellipse parameters found when measured H^+ beams are transformed back into the DT linac. To ascertain representative beam shapes from the DT linac, we have transformed 10 beam

TABLE I
EXPERIMENTAL ELLIPSE PARAMETERS AT ENTRANCE TO
QUADRUPOLE 157 IN 201.125-MHz LINAC

CASE	α_x	β_x	α_y	β_y
1	0.744	90.157	-1.013	0.381
2	1.163	0.216	-1.331	0.459
3	0.916	0.216	-1.416	0.499
4	0.939	0.211	-1.464	0.533
5	1.625	0.314	-1.592	0.536

measurements into the DT linac using TRACE. These measurements were taken during LAMPF production cycles 24-26. The ellipse parameters are shown in Table I. Of the 10 cases only 4 had the envelope shapes expected of matched beams in the linac; for example, the envelopes alternately had humps and waists as they traveled along the linac. A fifth case was marginal at best. One of the good cases that was often used as a representative input beam is shown in Fig. 3. The four good cases all have very similar beam shapes, and hence, we have assumed that this type of beam has the shape of a matched beam in the DT linac and that the new TR should have input range around this emittance shape. The exit ellipse parameters were assumed to be in the region of our present best estimate of the matched H^+ beam in the SC linac.

Once a quadrupole solution was found for a set of input and output conditions, the beam envelope was examined and accepted if, and only if,

Fig. 3.
Representative beam envelopes in the final section of
the DT linac.

- 1) the ratio of the x and y envelopes at any position was between 0.5 and 2.0 (This constraint is referred to as the peak-to-valley check; larger ratios can result in x-y coupling by way of quadrupole aberrations.),
- 2) the maximum size of the beam in the TR was ≤ 0.8 cm when the emittance area equaled 0.4π cm-mrad, and
- 3) the required quadrupole strengths or fields were ≤ 3.3 kG/cm.

For a given set of input and output conditions, a number of solutions were often found as we varied the initial TRANSPORT starting values of the quadrupole strengths. These solutions were grouped into families depending on the required magnitude and sign of the quadrupole fields and on the characteristic shapes of the beam envelopes. In some cases the number of families was >10 . We labeled a family "acceptable" if 1) it satisfied the above criteria over a range of input- and output-beam ellipse parameters, 2) its output-beam shape was relatively insensitive to small errors in quadrupole strengths and quadrupole positions, and 3) in the case of the long track its output-beam shape was relatively insensitive to changes in the longitudinal path length corresponding to a relative phase adjustment of $\pm 11^\circ$.

IV. METHODS OF FINDING SOLUTIONS

We tried a number of approaches to find quadrupole solutions for the three tracks. We shall first briefly discuss the approaches that failed and then discuss our final successful procedures. As stated earlier, the input-beam-ellipse parameters for the new TR were taken from LAMPF measurements at 100 MeV. The exit parameters were our best estimates of the matched parameters into the SC linac. The parameter values that we have been using with our present TR are given in Table II. The range of these exit parameters was found⁶ by taking matched beam conditions at the exit of Module 5 in the SC linac and running the beam upstream to the entrance of

TABLE II
MATCHED ELLIPSE PARAMETERS FOR THE SC LINAC

$\alpha_x = 0.337$	$\beta_x = 0.329$
$\alpha_y = 1.239$	$\beta_y = 0.556$

Module 5 for various settings of the Module 5 quadrupoles. We want our new TR to have the capability of matching the beam to a variety of these values.

We use the fitting code TRANSPORT for most of our searches for quadrupole strengths. This code, which uses a χ^2 fitting algorithm, has a number of disadvantages. 1) The quadrupole-strength step size can often be so large that the code jumps over a potential solution. 2) The code does not retain the lowest χ^2 of the series of trial fits and can give a set of final quadrupole strengths that are not the best that the code has found. 3) The first and second disadvantages can result in the code finding no solution when a solution is possible; for example, the fitting algorithm gets "lost" in χ^2 space. Versions of TRACE do exist that do not have the above problems, but they require large amounts of computer time and are impractical for large-scale searches. TRANSPORT is very fast, and for this reason we chose to use it. For special cases when TRANSPORT failed we often resorted to using TRACE.

In TRANSPORT the fitted parameters XMAX and SIGX are related to ellipse parameters by

$$XMAX = \sqrt{EB}$$

and

$$SIGX = E\alpha \quad .$$

The desired accuracy of a fit or standard deviation on the fitted beam-matrix elements was 0.01. We rejected fits with χ^2 values >1 . The solutions with χ^2 values of ~ 1 were usually sufficiently matched that they would be acceptable, but we found that when such χ^2 values occurred, the solutions would rapidly deteriorate as further changes in parameters were made.

Solutions can also be characterized by a mismatch factor F (Ref. 7) where

$$F = \frac{\Delta R}{R} \quad ,$$

R is the radius of the ideal matched emittance transformed into a circle, and

ΔR is the difference between the major and minor axis of the "real" emittance transformed into the same frame. In practice, F is obtained by measuring the residual betatron oscillations of the beam envelope at homologous points. There is no direct functional relationship between the χ^2 of TRANSPORT and F , but a χ^2 of 1 for a sample of cases corresponded to F values of about 0.05.

A. Short-Track Studies

The first attempts, which failed, dealt with the short-track quadrupole solutions that gave waists at the position of the bucket rotator. We were trying to minimize the size of the beam so as to minimize the longitudinal-transverse coupling in the bucket rotator. When the value of α was set to zero in the region of the bucket rotator, the solutions found with TRANSPORT were characterized by large quadrupole strengths and unacceptable beam-envelope shapes.

The next attempt was to make the values of β consistent with the minimal values found in the DT linac and in the SC linac. The value of α was left unconstrained. Again, the TRANSPORT code gave solutions with unacceptable quadrupole strengths and beam-envelope shapes. At this time the TR design called for quadrupoles Q1 and Q2 to be a doublet and quadrupoles Q3 and Q4 to be a doublet. This configuration is shown in Fig. 4.

Next we set the α parameter to equal zero and made β to be consistent with the minimal values in the two linacs. Quadrupoles Q3 and Q4 were set to values that gave smooth envelope behavior in the TR. The resulting beam,

Fig. 4.

An initial version of the proposed TR.

linac, did not have the required matched values. However, it was assumed that the quadrupoles in Module 5 could be used to match the beam by the time it arrived in Module 6. Quadrupoles Q1 and Q2 were made symmetric with Q3 and Q4. Because of the symmetry of the TR around its midpoint, the beam envelope now had the same smooth shape in the first half of the TR as it did in the last half. The new resulting beam-ellipse parameters at the exit of the DT linac were not characteristic of the measured values found earlier. The final quadrupoles Q159, Q161, Q163, and the to-be-installed Q165 in the DT linac were used to rematch the beam at the linac exit. An acceptable TRANSPORT solution was found, and quadrupoles Q157, Q1, and Q2 in the TR were adjusted to reduce the ratio of the x and y envelopes. The resulting fields in the last DT-linac quadrupoles are given in Table III. However, the existence of acceptable solutions was very dependent on the values of quadrupoles Q1 and Q2, and consequently the input range of the ellipse parameters at Q157 was too small. We assumed that the matching problem was ill conditioned for finding solutions in the input and exit spaces of interest. During these studies we used the particle-tracing code PARMILA, which models the DT linac, to verify that negligible errors are made when TRACE or TRANSPORT is used to model this final small section of the linac.

Following these unsuccessful attempts we modified the short-track design and split the two doublets into four singlets (Fig. 2). This modification reduced the long drift spaces, where no quadrupoles were present, and made the TR more similar in quadrupole placement to the two linacs. Our method of searching for solutions with TRANSPORT also changed. We knew that the

TABLE III
NEW QUADRUPOLE CURRENTS AND FIELD STRENGTHS

<u>Quadrupole No.</u>	<u>Current (A)</u>	<u>Gradient (g/cm)</u>
157	249	-679
159	264	722
161	251	-686
163	177	484
165	39	-107

possibility of a code finding types of solutions depended on the starting values of the quadrupoles to be varied. We had used intuition in choosing the initial values, but because of the complicated nature of the beam line, due in part to the large amounts of vertical focusing occurring in the bending magnets, intuition was not sufficient. A systematic four-dimensional search over the initial four quadrupole values was necessary. A command file QUIK2 (Appendix), which uses TRANSPORT as a subroutine, was set up for this purpose. We were limited in the number of initial quadrupole values n that could be tried for a particular set of input- and exit-ellipse parameters. Because the number of TRANSPORT runs equals n^4 , any value of $n > 3$ required prohibitive amounts of computer and calendar time. We made a number of trial runs with $n = 3$ and 4 and found that, with a step size in a quadrupole field of 600 G/cm, no additional solutions were found when n was increased from 3 to 4 with a corresponding decrease in step size. Test cases also showed that, if the starting value of a quadrupole was within 800 G/cm of a solution, TRANSPORT converged to a solution. Therefore, a step size of 600 G/cm was considered adequately small. Using our grid-search approach, we examined the possible input beam conditions from the DT linac by assuming that, at Q165, α equaled zero with a range of β values consistent with the expected size in the DT linac. Examining the resulting beam-envelope shapes and quadrupole strengths, we found that all fits were unacceptable. We then assumed the same above conditions at Q163 and allowed Q165 to assume various strengths. The resulting ellipse parameters at the entrance to the TR again resulted in quadrupole solutions whose fields were too large. After these two failures we abandoned the assumption that the α must be zero at the quadrupole centers.

We then fixed the linac quadrupole strengths to those given in Table III. Conducting grid searches using representative beam shapes taken from Table I, we found 13 families of which 3 had acceptable shapes and quadrupole strengths. These 13 families may not all be independent, because as the input- and output-ellipse parameters were changed, some types of families would no longer be present and others would appear. We could not always tell if an appearing family was a new family or a reappearance of a previously found family.

Because only finite computer time and calendar time were available for these studies, we limited our searches to a few potentially good families and to finite ranges of input- and output-beam parameter spaces. We could not

fully explore the fact that the range of a family was not only correlated in x- and y-ellipse parameters but also between the input- and output-ellipse parameter values.

Our input and output searches were conducted in the following manner. After choosing a family with its quadrupole solutions, we systematically varied the input values of α_x and β_x for fixed input values of α_y and β_y and used TRANSPORT to find solutions. The procedure was repeated for grid α_y and β_y values. The target-output parameters at the exit of the TR were kept the same and the input x- and y-ellipse parameters were varied. If no solution could be found or if the family configuration abruptly changed, the starting quadrupole values were changed to those found when adjacent values of α_x and β_x values resulted in successful fits. For this procedure we used the VAX command file TRANC (Appendix). Periodically during these searches, TRANSPORT quadrupole solutions were used in TRACE, and the beam envelopes were examined and subjected to the beam criteria discussed previously, for example, the maximum-size check and the peak-to-valley check. We found that these two criteria were usually violated if the quadrupole fields exceeded 1000 G/cm in the short track and 2000 G/cm in the long track.

The output or exit searches were conducted in a similar manner. In this case the input-ellipse parameters were fixed during the search and the output parameters were varied. The regions, where acceptable fits could be found, were then mapped out.

Two families were examined in detail. The first family had a (-+-) signed configuration over the major portion of its range. The (-) indicates a horizontally diverging quadrupole and the (+) indicates a horizontally converging quadrupole. In Figs. 5(a) and (b) we show the input range of beam-parameter space where acceptable solutions can be found. A beam-envelope plot for one solution in this family is shown in Fig. 6. Figures 7(a) and (b) show the input range of the second (+++) family. The range of this family is somewhat greater than that of the first. Because we limited our searches to regions around measured beam parameters, the total ranges of these families are not shown and are probably greater than that displayed in the figures. In some cases the aperture of the DT linac limited the beam size so that values of $\beta \gg 0.4$ are not possible. In Figs. 5 and 7 the input parameters are evaluated at the entrance to quadrupole Q157. The exit parameters for the search were

Figs. 5(a) and (b).
 Entrance range of solutions for the (-+++ quadrupole configuration in the short track.

Fig. 6
 Beam envelopes for the (-+++ quadrupole configuration in the short track.

Figs. 7(a) and (b).
Entrance range of solutions for the (+++) quadrupole configuration in the short track.

$$\alpha_x = 0.4 \quad \beta_x = 0.25$$

and

$$\alpha_y = 1.3, \quad \beta_y = 0.3 \quad .$$

These are the beam parameters at the entrance to the SC linac. Of the five measured beam shapes, which had believable behavior in the DT linac, four are within the input range of the new TR. The fifth shape was very dissimilar to the other four cases and was not indicative of a well-matched beam in the linac. Therefore, the inability to match this fifth case is not considered a serious problem. The quadrupole strengths for the displayed ranges are all relatively small and always have been <1000 G/cm.

Figs. 8(a) and (b).
Exit range of solutions for the $(-+++)$ quadrupole configuration in the short track.

In Figs. 8(a) and (b) we show the results of an output range search on the first family, and in Figs. 9(a) and (b) we show results of a search on the second family. For these cases, the input beam-ellipse parameters at Q157 were set to

$$\alpha_x = 1.3, \quad \beta_x = 0.2$$

and

$$\alpha_y = -1.4, \quad \beta_y = 0.4 \quad .$$

Again we limited the region of search. These figures show that the ranges of the two families partially overlap and that the total range of both is considerably greater than either individual range. In Table IV we show beam parameters for the SC linac that can be transformed to the matched beam by

Figs. 9(a) and (b).
Exit range of solutions for the (+---) quadrupole configuration in the short track.

simple adjustments to the Module 5 quadrupole fields. Using this table and Figs. 8 and 9, we find that, for the output range of α_y and β_y that we examined, all beams can be matched to the required α_x and β_x values shown in Table IV and can be matched with low quadrupole strengths. Our output searches indicate that successful matching to the SC linac could also be accomplished for values of β_y smaller than those examined in Table IV. To check if these families were relatively insensitive to quadrupole field and position errors, we examined the performance of the new TR when percentage errors of +1.0, -1.0, and 0.0 in quadrupole fields were introduced. Of all 81 combinations of errors, the worst case had a mismatch factor $F = 0.06$. The lengths of the various drifts were given +1- or -1-cm errors; and the worst mismatch factor F was 0.07. Both values of F are negligible. The check was done with input-ellipse parameters set to

TABLE IV
SOLUTIONS FOR MODIFIED 805-MHz LINAC

α_y	β_y								
	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
1.4			0.064	0.092	0.124	0.157	0.180	0.213	0.254
1.3		0.049	0.070	0.099	0.136	0.166	0.195	0.235	0.278
1.2		0.053	0.077	0.108	0.145	0.175	0.210	0.248	0.299
1.1			0.083	0.117	0.152	0.189	0.227	0.251	0.314
1.0									

α_y	β_y								
	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
1.4			0.167	0.335	0.414	0.436	0.385	0.374	0.352
1.3		-0.129	0.166	0.309	0.373	0.370	0.325	0.310	0.295
1.2		-0.108	0.147	0.269	0.310	0.325	0.300	0.238	0.298
1.1			0.125	0.229	0.273	0.269	0.262	0.189	0.263
1.0									

$$\alpha_x = 1.0, \quad \beta_x = 0.2$$

and

$$\alpha_y = -1.4, \quad \beta_y = 0.5 \quad ;$$

the exit parameters were set to

$$\alpha_x = 0.4, \quad \beta_x = 0.25$$

and

$$\alpha_y = 1.3, \quad \beta_y = 0.3 \quad ;$$

and the quadrupole solutions were

$$Q_1 = 659.0, \quad Q_2 = 643.7, \quad Q_3 = -524.8, \quad \text{and} \quad Q_4 = 472.8 \quad .$$

The dispersive qualities of the short track were examined. Only with no quadrupole fields is the TR truly nondispersive at its exit. For a representative tune, a 1% change in the momentum resulted in a 0.4-cm displacement in the horizontal position of the beam centroid. The only measurement⁸ of the LAMPF longitudinal emittance of 100 MeV indicated that 90% of the beam was contained within a momentum spread of $\pm 0.22\%$. The dispersion caused by this momentum spread would result in a beam broadening amounting to ± 0.08 cm in the transverse direction. This increase is small compared to the ± 0.6 -cm beam size measured at the 90% level. The worst displacement of the beam because of dispersion occurs at the center of the short track and is only slightly larger than 0.4-cm/% momentum. The dispersion is only slightly smaller in quadrupole Q4. With our increased clear aperture in the TR, this source of beam broadening should not cause any beam-scraping problems.

B. The Long-Track Studies

Similar input- and output-range searches were made for the long track as were made for the short track. In our initial searches the bending magnets BM05 and BM08 were set to full field strength; BM06 and BM07 were set to zero strength. This arrangement corresponds to the shortest path length in the long track. When the quadrupole solutions, which were found with this arrangement, were used with 3° bends in BM05 and BM08 and 17° bends in BM06 and BM07, the resulting mismatch factors in the vertical plane were huge and unacceptable. This behavior is the result of the nonnegligible amounts of vertical focusing that occurs in BM05-BM08 magnets. Another search was therefore made with 3 and 17° bends; these bends resulted in a path-length difference between the long and short tracks of approximately one-half of an 805-rf wavelength. In this search we found 12 families, 4 of which had acceptable solutions.

We have assumed that the long track will be used to transport the H^- beam. For this reason we have interchanged the x and y values of the ellipse parameters in all our searches. In the event that we wish to have H^+ traverse the long track, we will need to repeat all our input and output studies for

both the long and short tracks because the bending magnets, with their focusing in the vertical plane, destroy the symmetry or equivalence between the x and y planes of the H^+ and the y and x plane of the H^- . We hope that the beam-element configuration, which we have developed, will not be ill conditioned for rematching studies.

We have examined in detail the two best families. In Figs. 10(a) and (b) we show the input range of the first (+--+) family, and in Figs. 11(a) and (b) we show the input range of the second family (+-+-). The ranges of satisfactory solutions are very similar for these two cases and are much larger than those of the short track. The quadrupole field strengths are larger than those found in the short track, but the fields are always >2000 G/cm. In Fig. 12 we show a typical beam envelope in the long track.

The results of output searches for the two families are shown in Figs. 13(a) and (b) and 14(a) and (b). Comparing these plots with the desired ellipse parameters shown in Table IV, we see that over the regions explored

Figs. 10(a) and (b).
 Entrance range of solutions for the (+--+) quadrupole configuration in the long track.

Figs. 11(a) and (b).
Entrance range of solutions for the (+ +) quadrupole configuration in the long track.

Fig. 12.
Beam envelopes in the long track.

the new TR could match all beams except when $\alpha_x = +1.2$ and $\beta_x = 0.5$. The overlap between what the TR can supply and what is needed for the 805-MHz linac is very good; furthermore, this overlap probably exists beyond values of $\alpha_y = 1.4$.

The effects of dispersion in the long track were found to be one-half that of the short track at the entrance of the SC linac. The largest dispersion effect occurred in the center of the long track and corresponded to

Figs. 13(a) and (b).

(a)

Exit range of solutions for the (+--+)-quadrupole configuration in the long track.

(b)

Exit range of solutions for the (+--+)-quadrupole configuration in the long track.

1.21-cm/% momentum. Because the beam pipe is already large at this location to facilitate path-length changes, no dispersion-related beam-spill problems are anticipated.

Sensitivity studies were also made of the long-track configuration and tune. Errors of 1% in quadrupole strengths and 1 cm in drift lengths were used. The worst mismatch occurred when all four quadrupoles were in error by +1%; the value of F in this case was 0.1. A systematic error of +1 cm in 17 drift lengths only gave a mismatch of 0.05. Both of these mismatch factors are small.

The long track has a capability of changing the path length by 6.7 cm or 310° , assuming an rf frequency of 805 MHz. This amount is much greater than what actually is needed; typically $\pm 11^\circ$ adjustment around zero phase is sufficient. Here zero phase difference is defined as occurring when the H^- arrives at the SC linac later than the H^+ by exactly an odd multiple of one-half 805-MHz rf cycles. Whereas changing the path length is in itself not

Figs. 14(a) and (b).
Exit range of solutions for the (+++) quadrupole
configuration in the long track.

sufficient to change the transverse-emittance shape at the TR exit, the large amount of vertical focusing in the bending magnets causes the beam shape to be very dependent on path length. Changes of $\pm 11^\circ$ in longitudinal phase were examined and found to cause a transverse mismatch characterized by a value of $F = 0.1$. This is an acceptable value, and therefore we can make such longitudinal adjustments without rematching the transverse emittance. The mismatch factor examined for phase adjustments for $\pm 40^\circ$ proved unacceptable.

C. The Straight-Through Section

We used a different approach for finding acceptable families of solutions in the straight-through section. From the input and output conditions and the quadrupole placements, we deduced that a (-++) quadrupole configuration would yield an acceptable solution. Using TRACE we were almost able to find a match by a trial-and-error selection of quadrupole-field gradients in the TR. When our best selection was used for starting values in the matching portion of TRACE, TRACE quickly converged to a good fit.

The results of our input-range search are shown in Figs. 15(a) and (b). The range of acceptable solutions is less than that of either the long track or the short track. However, the range is sufficient to conclude the consistent four measurements of the beam parameter given in Table I. The major cause of our reduced input range is the beam-size limit. In some cases, because of the diverging nature of the input beam and the long drift distance between the exit of the linac and the first quadrupole, the beam exceeds the 0.8-cm limit before it reaches the first quadrupole in the TR. The long drift cannot be shortened because it is impossible to physically move the first quadrupole upstream. In other cases the beam becomes too large in the x plane after the first quadrupole, which is a horizontally diverging quadrupole. The effects of the size limit can be reduced by moving the second quadrupole upstream closer to the first and the third quadrupole downstream closer to the fourth. But for this configuration, the region of parameter space, where

Figs. 15(a) and (b).
Entrance range of solutions for the (---) quadrupole configuration in the straight-through section.

solutions could be found, was significantly reduced. Therefore, we decided to use a larger separation and to have a larger input range of ellipse parameters where acceptable solutions can be found at the expense of having larger beam envelopes in the TR. The average increase in beam-envelope diameter was 2 mm. The vertical focusing in the long- and short-track bending magnets has the beneficial effect of shortening the distance between the exit of the linac and the first focusing element, thereby reducing the beam size in these two tracks.

In Figs. 16(a) and (b) we show the output range of acceptable solutions. This range is much larger than either the long or short tracks. As in the input-range search, this range is reduced by decreasing the separation between the first and second quadrupoles and between the third and fourth quadrupoles. Comparing these figures in Table IV, we see that we have a good overlap with what the TR can deliver and what the SC linac will accept in beam parameter space. We know that if the H^+ and H^- are matched to the DT linac and if our

Figs. 16(a) and (b).
Exit range of solutions for the $(-++)$ configuration in the straight-through section.

assumption that the matched H^- beam will have the same shape as that of the H^+ beam with the x and y plane interchanged, then the straight-through section will equally match both the H^+ and H^- beams.

The straight-through section also proved to be insensitive to errors in quadrupole strength and positions. When the field error was limited to +1, -1, and 0% values, the worst mismatch occurred when all quadrupoles were +1% high. The mismatch factor was 0.13. With position errors, the worst mismatch occurred when the 10 drift spaces in the straight-through section were increased by +1 cm. The mismatch factor then was only 0.08. The particular tune used in this study had input parameters equal to

$$\alpha_x = 1.0, \quad \beta_x = 0.2$$

and

$$\alpha_y = -1.4, \quad \beta_y = 0.5 \quad ,$$

and output parameters equal to

$$\alpha_x = 0.4, \quad \beta_x = 0.25 \quad ,$$

and

$$\alpha_y = 1.3, \quad \beta_y = 0.3 \quad .$$

The quadrupole-field gradients, measured in Gauss/centimeter, were

$$Q_1 = -1113, \quad Q_2 = 1252, \quad Q_3 = 485, \quad \text{and} \quad Q_4 = -882 \quad .$$

V. LONGITUDINAL PHASE ADJUSTMENTS

As mentioned earlier, the arrival time at the SC linac or the longitudinal phase of the beam that traverses the long track can be adjusted with just one knob controlling a power supply. Such adjustments will not affect the beam in the short track. Any phase adjustment to the beam that

traverses the short track can only be made by changing the relative phase between the radio frequency of the two linacs. Such adjustments will also change the phase of the beam in the long track. Numerous constraints have prevented us from making the phasing of the two beams completely independent. However, an important improvement in the new TR design is that the phasing of the two beams would be only a two-knob problem. The relative phase of the two beams at the exit of the TR vs the magnetic fields in the long-track magnets is shown in Fig. 17. In this figure we have again defined zero relative phase difference occurring when the two beams arrive at the SC linac with absolute phases that differ by odd multiples of 180° ; that is, if the relative phase difference equals zero and if the H^+ arrives exactly at the synchronous phase, then the H^- will also arrive exactly at its synchronous phase.

Fig. 17.
Relative longitudinal phase ϕ vs bending magnet fields.

VI. STEERING MAGNET FIELDS IN THE NEW TR

The steering-magnet fields have been calculated for various configurations in the long and short tracks of the new TR. For the various configurations tried, only the functions of the steering magnet changed, from horizontal to vertical bending or vice versa; the positions of the magnets did not change. The long- and short-track quadrupoles were set to one of the good solutions found when the input- and output-beam-ellipse parameters were chosen in the middle of their usable ranges. The parameters were the same for both tracks.

Table V contains short-track magnetic-field values that are required to give position (cm) and angular (mr) displacements of the beam centroids at the entrance to the SC linac. The fields are given in kilogauss, with the assumption of an effective length of 10.5 cm. We generated this table assuming a VHHV configuration; that is, the first steering magnet is vertical followed by two horizontal-steering magnets and ending with a vertical-steering magnet. This table also shows that fields can become excessively high for portions of the horizontal displacement range. In Table VI we changed the order of the steering magnets to HVVH configuration. As expected, the higher fields now occur in the vertical-steering magnets, although the maximum fields are somewhat reduced. In Table VII we changed the configuration to HVHV so that both the horizontal- and vertical-magnet pairs were separated by approximately equal distances. The first magnet remained a horizontal type to facilitate the installation of carbon absorbers. As expected, the horizontal situation deteriorated somewhat but the vertical case improved. This HVHV is the best configuration because now both planes have acceptable ranges of adjustments with steering magnets whose maximum integral $\int B dl$ is 20 kG cm.

Table VIII gives field strengths for the long track in the VHHV configuration. All centroid displacements can be accommodated with 20 kG-cm magnets. In Table IX we show the results of the HVVH configuration, which satisfies the condition that the first steering magnet be a horizontal type. The differences between Tables VIII and IX are small and reflect the fact that these changes in position are relatively small compared to the total separation of the magnet pairs. Some reduction in the vertical-steering magnets could be gained by changing to a HVHV configuration. However, either configuration using 20 kG cm magnets will satisfy our needs.

TABLE V

STEERING-MAGNET FIELDS FOR THE SHORT-TRACK
VHHV CONFIGURATION

$x'(\text{mr})$	Horizontal Fields (kG)				
	$x(\text{cm})$				
	-1.0	-0.5	0.	0.5	1.0
10	3.650 ^a	-3.015	-2.38	-1.745	-1.110
	2.969 ^b	2.674	2.38	2.086	1.791
5	-2.460	-1.825	-1.19	-0.555	0.080
	1.779	1.484	1.19	0.896	0.601
0				0.637	1.27
				-0.294	-0.589

$$^a_{H1} (\text{in kilogauss}) = 1.27x - 0.238x'.$$

$$^b_{H2} (\text{in kilogauss}) = 0.589x + 0.238x'.$$

$y'(\text{mr})$	Vertical Fields (kG)				
	$y(\text{cm})$				
	-1.0	-0.5	0.	0.5	1.0
10	-0.987 ^a	-0.754	-0.520	-0.286	-0.053
	1.943 ^b	1.861	1.780	1.698	1.617
5	-0.727	-0.494	-0.260	-0.026	0.207
	1.053	0.972	0.890	0.808	0.727
0				0.234	0.467
				-0.082	-0.169

$$^a_{V1} (\text{in kilogauss}) = 0.467y - 0.052y'.$$

$$^b_{V2} (\text{in kilogauss}) = 0.163y + 0.178y'.$$

We made similar calculations for the straight-through section and examined both the HVVH and the VHHV configurations. In both cases the horizontal-steering magnets required greater fields; therefore, we chose the HVVH case because it required the lower magnetic fields in the horizontal-steering magnets. Table X shows magnetic fields needed to give various position and angular displacements at the entrance to the SC linac. We see that high fields are required in the straight-through section and that, if a magnetic-field strength limit of 2.7 kG is imposed, we will have much

TABLE VI
STEERING-MAGNET FIELDS FOR THE SHORT-TRACK
(HVVH) CONFIGURATION

$x'(mr)$	Horizontal Fields (kG)				
	$x(cm)$				
	-1.0	-0.5	0.	0.5	1.0
10	1.558 ^a 1.723 ^b	1.194 1.665	-0.93 -1.61	-0.466 1.5535	-0.102 1.497
5	-1.143 0.918	-0.779 0.9615	-0.415 0.825	-0.051 0.7485	0.313 0.692
0				0.364 -0.057	0.728 -0.115

^aH1 (in kilogauss) = $0.728x - 0.083x'$.

^bH2 (in kilogauss) = $0.113x + 0.161x'$.

$y'(mr)$	Vertical Fields (kG)				
	$y(cm)$				
	-1.0	-0.5	0.	0.5	1.0
10	-1.834 ^a 2.932 ^b	-1.657 2.951	-1.42 2.97	-1.183 2.989	-0.946 3.008
5	-1.184 1.447	-0.947 1.466	-0.71 1.485	-0.473 1.504	-0.236 1.523
0				0.237 0.019	0.474 0.038

^aV1 (in kilogauss) = $0.474y - 0.142y'$.

^bV2 (in kilogauss) = $0.038y + 0.297y'$.

steering in the straight-through section when compared with the other two tracks.

VII. POSITION CHANGES AND STUDIES

After the various studies were made of the long track, the short track, and the straight-through sections, the positions of some of the magnets were changed to assure that all the components would fit into the available space. These placement changes were as large as 8 cm and were greater than those made in our sensitivity test. The changes made in the long track were so large that new bend angles were needed in the BM05-BM08 bending magnets. The new

TABLE VII
STEERING-MAGNET FIELDS FOR THE SHORT-TRACK
(HVHV) CONFIGURATION

<u>x'(mr)</u>	<u>Horizontal Fields (kG)</u>				
	<u>x(cm)</u>				
	<u>-1.0</u>	<u>-0.5</u>	<u>0.</u>	<u>0.5</u>	<u>1.0</u>
10	-2.216 ^a 1.579 ^b	-1.830 1.527	-1.444 -1.475	-1.058 1.423	-0.672 1.371
5	-1.494 0.842	-1.108 0.790	-0.722 0.735	-0.336 0.685	0.050 0.633
0				0.386 -0.052	0.772 -0.104

^aH1 (in kilogauss) = 0.772x - 0.144x.

^bH2 (in kilogauss) = -0.104x + 0.147x'.

<u>y'(mr)</u>	<u>Vertical Fields (kG)</u>				
	<u>y(cm)</u>				
	<u>-1.0</u>	<u>-0.5</u>	<u>0.</u>	<u>0.5</u>	<u>1.0</u>
10	-1.026 ^a 1.560 ^b	-0.783 1.570	-0.54 1.58	-0.297 1.590	-0.054 1.600
5	-0.756 0.770	-0.513 0.780	-0.27 0.790	-0.027 0.800	0.216 0.810
0				0.243 0.0101	0.486 0.0202

^aV1 (in kilogauss) = 0.485y - 0.054y'.

^bV2 (in kilogauss) = 0.0202y + 0.158y'.

bend angles, 4° for BM05 and BM08 and 16° for BM06 and BM07, now give the correct path length for the proper longitudinal phasing of the two beams.

The effects of these changes were examined in the following manner. Typical input-ellipse parameters, which could be matched with good solutions, were transformed through the modified lines with new magnet positions but with quadrupole strengths found with the unmodified lines. The outputs were compared with those found earlier. The worst mismatch factor F was 1) 0.09 for the short track, 2) 0.13 for the long track, and 3) 0.08 for the straight-through section. These are not large values, so we expect that new exact solutions will not differ significantly from the original values and

TABLE VIII

STEERING-MAGNET FIELDS FOR THE LONG-TRACK
(VHHV) CONFIGURATION

$x'(\text{mr})$	Horizontal Fields (kG)				
	$x(\text{cm})$				
	-1.0	-0.5	0.	0.5	1.0
10	-0.814 ^a 1.416 ^b	-0.613 1.438	-0.413 1.460	-0.213 1.482	-0.012 1.505
5	-0.607 0.686	-0.407 0.708	-0.207 0.730	-0.006 0.752	0.194 0.775
0				0.200 0.023	0.401 0.045

^aH1 (in kilogauss) = $0.4006x - 0.0413x'$.

^bH2 (in kilogauss) = $0.0445x + 0.146x'$.

$y'(\text{mr})$	Vertical Fields (kG)				
	$y(\text{cm})$				
	-1.0	-0.5	0.	0.5	1.0
10	-1.030 ^a 1.885 ^b	-0.753 1.778	-0.475 1.670	-0.199 1.562	-0.078 1.455
5	-0.792 1.050	-0.515 0.942	-0.238 0.835	0.039 0.723	0.316 0.620
0				0.277 -0.107	0.554 -0.215

^aV1 (in kilogauss) = $0.554y - 0.0476y'$.

^bV2 (in kilogauss) = $-0.215y + 0.167y'$.

that the input and output ranges will not need to be reduced. This expectation should be verified.

VIII. CONCLUSION

We presented a new TR design that avoided many of the problems of our present TR. We now have the capacity to independently match the H^+ and the H^- beams in LAMPF. We have greatly simplified the longitudinal phasing of the two beams and have greatly increased our beam-measurement capability. We have made beam-dynamic studies of the new three lines in the TR. We found

TABLE IX
STEERING-MAGNET FIELDS FOR THE LONG-TRACK
(HVVH) CONFIGURATION

<u>x'(mr)</u>	<u>Horizontal Fields (kG)</u>				
	<u>x(cm)</u>				
	<u>-1.0</u>	<u>-0.5</u>	<u>0.</u>	<u>0.5</u>	<u>1.0</u>
10	-0.762 ^a 1.391 ^b	-0.561 1.420	-0.36 1.45	-0.159 1.480	0.045 1.509
5	-0.582 0.666	-0.381 0.696	-0.18 0.725	0.081 0.754	0.222 0.784
0				0.201 0.0295	0.402 0.059

^aH1 (in kilogauss) = 0.402x - 0.036x'.

^bH2 (in kilogauss) = 0.059x + 0.145x'.

<u>y'(mr)</u>	<u>Vertical Fields (kG)</u>				
	<u>y(cm)</u>				
	<u>-1.0</u>	<u>-0.5</u>	<u>0.</u>	<u>0.5</u>	<u>1.0</u>
10	-1.198 ^a 2.087 ^b	-0.899 1.948	-0.6 1.81	-0.301 1.672	-0.002 1.533
5	-0.878 1.182	-0.599 1.044	3 9.05	-0.001 0.766	0.298 0.628
0				0.299 -0.138	0.598 -0.277

^aV1 (in kilogauss) = 0.598y - 0.060y'.

^bV2 (in kilogauss) = -0.277y + 0.181y'.

quadrupole placements that were consistent with our space constraints, that had large regions of input- and output-beam spaces that could be matched, and that were insensitive to errors. After examination of the output ranges of the three lines and the table of acceptable input-ellipse parameters to the SC linac, we have selected new ellipse parameters for the beam at the entrance to the SC linac. The new parameters are given in Table XI and should result in a good beam behavior in all three lines of the TR and in the SC linac.

TABLE X
STEERING-MAGNET FIELDS FOR THE STRAIGHT-THROUGH
(HVVH) CONFIGURATION

<u>x'(mr)</u>	<u>Horizontal Fields (kG)</u>				
	<u>x(cm)</u>				
	<u>-1.0</u>	<u>-0.5</u>	<u>0.</u>	<u>0.5</u>	<u>1.0</u>
10	-5.451 ^a 6.403 ^b	-4.495 5.503	-3.540 4.602	-2.584 3.702	-1.628 2.801
5	-3.681 4.102	-2.726 3.202	-1.770 2.301	-0.814 1.400	0.141 0.500
0				0.956 -0.901	1.912 1.801

^aH1 (in kilogauss) $1.912x - 0.3540x'$.

^bH2 (in kilogauss) $-1.8012x + 0.4602x'$.

<u>y'(mr)</u>	<u>Vertical Fields (kG)</u>				
	<u>y(cm)</u>				
	<u>-1.0</u>	<u>-0.5</u>	<u>0.</u>	<u>0.5</u>	<u>1.0</u>
10	-3.440 ^a 3.860 ^b	-2.890 3.538	2.340 3.210	-1.790 2.882	-1.240 2.554
5	-2.270 2.261	-1.720 1.933	-1.170 1.605	-0.620 1.277	-0.07 0.949
0				0.550 -0.328	1.10 -0.656

^aV1 (in kilogauss) $= 1.10y - 0.234y'$.

^bV2 (in kilogauss) $= -0.656y + 0.321y'$.

TABLE XI
NEW MATCHED ELLIPSE PARAMETERS FOR THE SC LINAC

<u>α_x</u>	<u>β_x</u>	<u>α_y</u>	<u>β_y</u>
0.37	0.166	1.3	0.35

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APPENDIX

COMPUTER CODES AND PROCEDURAL FILES

All the searches made in the new TR studies were done using the MPVAX1 computer in Lab-Office Building. We constructed a command file QUIK2.COM, which 1) ran TRANSPORT; 2) made a four-dimensional grid search over the four

starting values of the quadrupoles in the new TR; and 3) checked to see if the TRANSPORT generated fit had a χ^2 value <1 and, if so, printed out the quadrupole solutions and the corresponding χ^2 . A listing of this file is shown in Fig. A-1. This file (input data file QCHC.DAT) represents a portion of the straight-through section beginning at the first quadrupole and ending at the last quadrupole in this section. A listing of QCHC.DAT is shown in Fig. A-2, and its corresponding short-track file QCH1 is shown in Fig. A-3. This file can be used by replacing QCHC with QCH1 in the QUIK2.COM command file. The COPY command and statements 17 and 18 of Fig. 17 also must be

```

1 $set noverify
2 $TEDI QCHC.DAT
3 T3,4;T14,17;END
4 $SET WORKING_SET/LIMIT=200
5 $COUNT=0
6 $START:
7 $COUNT=COUNT+1
8 $WRITE SYSS$OUTPUT "COUNT IS'"COUNT'"
9 $ASSIGN NLAO: SYSS$OUTPUT
10 $ASSIGN Q14P.DAT FOR004
11 $RUN QUIK2.EXE
12 $OPEN FOR003 1OR003.DAT
13 $READ FOR003 LIN2E2
14 $CLOSE FOR003
15 $IF "'F$EXTRACT(0,1,LIN2E2)'" .EQS. "N" THEN EXIT
16 $TEDI QCHC.DAT
17 NV;DL5;CFA2,0;FOR003.DAT;DL7;CFA3,0;FOR003.DAT;
18 DL9;CFA4,0;FOR003.DAT;DL11;CFA5,0;FOR003.DAT;END
19 $PURGE QCHC.DAT
20 $DEASSIGN FOR004
21 $Q{MP13}TRNSPT QCHC.DAT TR2.OUT
22 $IDEASSIGN SYSS$OUTPUT
23 $ASSIGN NLAO: SYSS$OUTPUT
24 $MCR EDI TR2.OUT
25 PL COV&SAV 1 ZOO2.DAT
26 SAV 1 ZOO2.DAT
27 $OPEN ZOO2 ZOO2.DAT
28 $READ ZOO2 LIN2
29 $CLOSE ZOO2
30 $DEASSIGN SYSS$OUTPUT
31 $TEDI TR2.OUT
32 T1,60;END
33 $IF "'F$EXTRACT(27,1,LIN2)'" .EQS. "+" THEN GOTO CONT
34 $TEDI TR2.OUT
35 NV;RP*; ; RP*; ; RP*; ; RP*; ; RP*; ; RP*; ; SV
36 NV;RP*; ; SV;TPA80,9;"QUA;TP*;COV;QUIT
37 $CON1:
38 $DELETE TR2.OUT;*
39 $DELETE Q14P.DAT;*
40 $DELETE ZOO2.DAT;*
41 $RENAME FOR003.DAT Q14P.DAT
42 $GOTO START
43 $EXIT
*
```

Fig. A-1.
A listing of the QUIK2.COM command file.

```

1 "RUN CENTRAL LINE FROM QUAD1 TO QUAD4"
2 0
3 1.0 0.49598 1.26596 .69570 1.52946 0.0 0.0 .44456 ;
4 12.0 +0.77083 0.0 0.0 0.0 0.0 +0.92665 ;
5 5.01 .112 -4.24130 3.81 "QUA1" ;
6 3.0 0.116 "DRE1" ;
7 3.0 0.1635 "DRE" ;
8 3.0 .1162 "DRE" ;
9 5.01 .112 +4.76500 3.81 "QUA2" ;
10 3.0 .3877 "DRE2" ;
11 5.01 .112 +1.84720 3.81 "QUA3" ;
12 3.0 .1162 "DRE4" ;
13 3.0 0.1635 "DRE" ;
14 3.0 .1162 "DRE" ;
15 5.01 .112 -3.33000 3.81 "QUA4" ;
16 13.0 1.0 ;
17 13.0 4.0 ;
18 10.0 1. 1. .44497 0.01 "XMAX" ;
19 10.0 3. 3. .61351 0.01 "YMAX" ;
20 10.0 2. 1. -0.5629 0.01 "ALPX" ;
21 10.0 4. 3. -1.0908 0.01 "ALPY" ;
22 SENTINEL
*
```

Fig. A-2.

A listing of the QCHC.DAT data file representing the straight-through track.

```

1 "RUN H+ FROM QUAD 1 TO QUAD 2 MODIFIED"
2 0
3 1.0 +0.40644 1.34734 +0.56568 0.70894 0.0 0.0 .44456 ;
4 12.0 +.68297 0.0 0.0 0.0 0.0 -.07181 ;
5 16.0 5 3.175 "GAP" ; 16.0 7 0.45 "K1" ; 16.0 8 2.8 "K2" ;
6 5.01 .112 -0.23400 3.81 "QUA1" ;
7 3.0 0.247 "DRE2" ;
8 2.0 20.0 "EDGE" ;
9 4.0 0.436 11.87216 0.0 "BEN2" ;
10 2.0 0.0 "EDGE" ;
11 3.0 0.100 "DRE3" ;
12 3.0 0.20 "DRE4" ;
13 5.01 .112 +1.48400 3.81 "QUA2" ;
14 3.0 0.44 "DRE5" ;
15 3.0 0.44 "DRE6" ;
16 5.01 .112 +1.40000 3.81 "QUA3" ;
17 3.0 0.20 "DRE7" ;
18 3.0 0.10 "DRE8" ;
19 2.0 0. "EDGE" ;
20 4.0 0.436 11.87216 0.0 "BEN3" ;
21 2.0 20.0 "EDGE" ;
22 3.0 .247 "DRE9" ;
23 5.01 .112 -0.65450 3.81 "QUA4" ;
24 13.0 1.0 ;
25 13.0 4.0 ;
26 10.0 1. 1. .34176 0.01 "XMAX" ;
27 10.0 3. 3. 0.46303 0.01 "YMAX" ;
28 10.0 2. 1. -0.3976 0.01 "ALPX" ;
29 10.0 4. 3. -.26320 0.01 "ALPY" ;
30 SENTINEL
*
```

Fig. A-3.

A listing of the QCH1.DAT data file representing the short track.

changed. In Fig. A-4 we show the input data file for the long track with 3° bends. The input-ellipse parameters in these three data files are found by running TRACE forward from quadrupole Q157 in the DT linac to the first quadrupole in the new TR line of interest. The output-ellipse parameters from TRACE are used to generate the input parameters for TRANSPORT. The fitted output-ellipse parameters of TRANSPORT are found by running TRACE backward from the entrance of the SC linac to the last quadrupole in the new TR line of interest. The output-ellipse parameters of TRACE are then used to generate the fitted output parameters in TRANSPORT. In the command file QUIK2.COM we use the FORTRAN code QUIK2.FOR, which steps through the starting quadrupole values and helps terminate the job when the range has been covered. A listing of this code is shown in Fig. A-5. We found that it was most convenient to run the QUIK2.COM command file in the BATCH mode and thereby have the option of running other codes interactively.

A second command file TRANC.COM was used to run TRANSPORT interactively. It saved a large amount of user time by automatically calling up the TRANSPORT input and output files using the text editor TEDI. A listing of this file is shown in Fig. A-6.

The beam envelopes of the TR solutions were examined using the version of TRACE on the MPVAX1 computer. This can be run by entering TRACE at a terminal if a LOGIN file exists with the statement

```
$ TRACE:==RUN DBA1:[AT2CWW.TRACE]TRACE.
```

The input file for the short track is called LNTRP.DAT (a display of the beam elements is shown in Fig. A-7). Similar files LNTRCEN and LNTRC3 exist for the straight-through section and for the long track with 3° and 17° bends. These files are shown in Figs. A-8 and A-9, respectively. In each case beams are transformed from the entrance of Q157, a quadrupole in drift-tube No. 157, to the entrance of the SC linac.

The results of the numerous TRANSPORT and TRACE computer runs are contained in three volumes of output data. These data are located in the

```

1 "RUN H- FROM QUAD1 TO QUAD4, 201 MODIFIED"
2 0
3 1.0 0.59498 1.62773 .40497 0.99591 0.0 0.0 .44456 ;
4 12.0 +0.91072 0.0 0.0 0.0 0.0 -.12794 ;
5 16.0 5 3.175 "GAP" ; 16.0 7 0.45 "K1" ; 16.0 8 2.80 "K2" ;
6 5.01 .112 +4.40974 3.81 "QUA1" ;
7 3.0 0.088 "DRG1" ;
8 5.01 .112 -3.76876 3.81 "QUA2" ;
9 3.0 0.10 "DRF2" ;
10 20. 180.0 ;
11 2.0 20.0 "EDGE" ;
12 4.0 .4503 1.7241 "BEN1" ;
13 2.0 -17.0 "EDGE" ;
14 20. -180.0 ;
15 3.0 0.1042 "DRF3" ;
16 20.0 180.0 ;
17 2.0 17.0 "EDGE" ;
18 4.0 .4333 10.1529 0.0 "BEN2" ;
19 2.0 0.0 "EDGE" ;
20 20.0 -180.0 ;
21 3.0 0.15 "DRF4" ;
22 20.0 180.0 ;
23 2.0 0.0 "EDGE" ;
24 4.0 .4333 10.1529 0.0 "BEN3" ;
25 2.0 17.0 "EDGE" ;
26 20.0 -180.0 ;
27 3.0 .1042 "DRF5" ;
28 20.0 180.0 ;
29 2.0 -17.0 "EDGE" ;
30 4.0 .4503 1.7241 "BEN4" ;
31 2.0 20.0 "EDGE" ;
32 20.0 -180.0 ;
33 3.0 .10 "DRF6" ;
34 5.01 .112 +3.53812 3.81 "QUA3" ;
35 3.0 0.088 "DRF7" ;
36 5.01 .112 -1.57116 3.81 "QUA4" ;
37 13.0 1.0 ;
38 13.0 4.0 ;
39 10.0 1. 1. .50279 0.01 "XMAX" ;
40 10.0 3. 3. .34814 0.01 "YMAX" ;
41 10.0 2. 1. -0.9312 0.01 "ALPX" ;
42 10.0 4. 3. -.1088 0.01 "ALPY" ;
43 SENTINEL

```

*

Fig. A-4.

A listing of the QCHM3.DAT data file representing the long track with 3^o bends.

author's office (MPF-6, Rm. 307) and should be useful as initial quadrupole fields to be used in the new TR when it is installed.

```

1 "RUN H- FROM QUAD1 TO QUAD4, 2E1 MODIFIED"
2 0
3 1.0 0.59498 1.62773 .40497 0.99591 0.0 0.0 .44456 ;
4 12.0 +0.91072 0.0 0.0 0.0 0.0 -.12794 ;
5 16.0 5 3.175 "GAP" ;16.0 7 0.45 "K1" ;16.0 8 2.80 "K2" ;
6 5.01 .112 +4.40974 3.81 "QUA1" ;
7 3.0 0.088 "DRG1" ;
8 5.01 .112 -3.76876 3.81 "QUA2" ;
9 3.0 0.10 "DRI2" ;
10 20. 180.0 ;
11 2.0 20.0 "EDGE" ;
12 4.0 .4503 1.7241 "BEN1" ;
13 2.0 -17.0 "EDGE" ;
14 20. -180.0 ;
15 3.0 0.1042 "DRI3" ;
16 20.0 180.0 ;
17 2.0 17.0 "EDGE" ;
18 4.0 .4333 10.1529 0.0 "BEN2" ;
19 2.0 0.0 "EDGE" ;
20 20.0 -180. ;
21 3.0 0.15 "DRI4" ;
22 20.0 180.0 ;
23 2.0 0.0 "EDGE" ;
24 4.0 .4333 10.1529 0.0 "BEN3" ;
25 2.0 17.0 "EDGE" ;
26 20.0 -180.0 ;
27 3.0 .1042 "DRI5" ;
28 20.0 180.0 ;
29 2.0 -17.0 "EDGE" ;
30 4.0 .4503 1.7241 "BEN4" ;
31 2.0 20.0 "EDGE" ;
32 20.0 -180.0 ;
33 3.0 .10 "DRI6" ;
34 5.01 .112 +3.53812 3.81 "QUA3" ;
35 3.0 0.088 "DRI7" ;
36 5.01 .112 -1.57116 3.81 "QUA4" ;
37 13.0 1.0 ;
38 13.0 4.0 ;
39 10.0 1. 1. .50279 0.01 "XMAX" ;
40 10.0 3. 3. .34814 0.01 "YMAX" ;
41 10.0 2. 1. -0.9312 0.01 "ALPX" ;
42 10.0 4. 3. -.1086 0.01 "ALPY" ;
43 SENTINEL

```

Fig. A-5.
A listing of the QUIK2.FOR FORTRAN file.

```

1 $ START:
2 $ @[MPI3]TRNSPT QCHC.DAT TR.OUT
3 $ TEDN TR.OUT
4 1P*/COV
5 1P*;FAIL;NV;KP*; ; RP*; ; RP*; ; SV
6 TPA120,5;QUAD
7 QUIT
8 $ INQUIRE ANS "DO YOU WANT TO LOOK AT OUTPUT FILE"
9 $ IF ANS .EQS. "N" THEN COTO EDIT_INPUT
10 $ assign/user_mode sys$command sys$input
11 $ TEDN TR.OUT
12 $ EDIT_INPUT:
13 $ INQUIRE ANS "DO YOU WANT TO EDIT INPUT FILE"
14 $ IF ANS .EQS. "N" THEN EXIT
15 $ ASSIGN/USER SYSS$COMMAND SYSS$INFUT
16 $ TEDN QCHC.DAT
17 $DELETE TR.OUT;*
18 $PURGE QCHC.DAT
19 $ GOTO START

```

Fig. A-6.
A listing of the TRANC.COM command file.

```

DSTP
# TRANSPORT ELEMENTS # PARAMETERS
1 QUADRUPOLE 2 -679.200 17.600 0.000 0.000 0.000
2 DRIFT 1 53.022 0.000 0.000 0.000 0.000
3 DRIFT 1 53.286 0.000 0.000 0.000 0.000
4 QUADRUPOLE 2 722.360 17.600 0.000 0.000 0.000
5 DRIFT 1 107.360 0.000 0.000 0.000 0.000
6 QUADRUPOLE 2 -686.650 17.600 0.000 0.000 0.000
7 DRIFT 1 108.400 0.000 0.000 0.000 0.000
8 QUADRUPOLE 2 484.270 17.600 0.000 0.000 0.000
9 DRIFT 1 106.680 0.000 0.000 0.000 0.000
10 DRIFT 1 2.747 0.000 0.000 0.000 0.000
11 QUADRUPOLE 2 -106.840 17.600 0.000 0.000 0.000
12 DRIFT 1 23.900 0.000 0.000 0.000 0.000
13 EDGE ANGLE 4 0.000 -124.900 0.450 2.800 3.175
14 BENDING MAGNET 3 -20.000 -124.900 0.000 0.000 0.000
15 EDGE ANGLE 4 -20.000 -124.900 0.450 2.800 3.175
16 DRIFT 1 22.000 0.000 0.000 0.000 0.000
17 QUADRUPOLE 2 65.930 11.200 0.000 0.000 0.000
18 DRIFT 1 24.709 0.000 0.000 0.000 0.000
19 EDGE ANGLE 4 20.000 124.900 0.450 2.800 3.175
20 BENDING MAGNET 3 20.000 124.900 0.000 0.000 0.000
21 EDGE ANGLE 4 0.000 124.900 0.450 2.800 3.175
22 DRIFT 1 10.000 0.000 0.000 0.000 0.000
23 DRIFT 1 11.200 0.000 0.000 0.000 0.000
24 DRIFT 1 8.800 0.000 0.000 0.000 0.000
25 QUADRUPOLE 2 643.670 11.200 0.000 0.000 0.000
26 DRIFT 1 44.000 0.000 0.000 0.000 0.000
27 DRIFT 1 44.000 0.000 0.000 0.000 0.000
28 QUADRUPOLE 2 -524.750 11.200 0.000 0.000 0.000
29 DRIFT 1 8.800 0.000 0.000 0.000 0.000
30 DRIFT 1 11.200 11.200 0.000 0.000 0.000
31 DRIFT 1 10.000 0.000 0.000 0.000 0.000
32 EDGE ANGLE 4 0.000 124.900 0.450 2.800 3.175
33 BENDING MAGNET 3 20.000 124.900 0.000 0.000 0.000
34 EDGE ANGLE 4 20.000 124.900 0.450 2.800 3.175
35 DRIFT 1 24.709 11.200 0.000 0.000 0.000
36 QUADRUPOLE 2 472.810 11.200 0.000 0.000 0.000
37 DRIFT 1 22.000 0.000 0.000 0.000 0.000
38 EDGE ANGLE 4 -20.000 -124.900 0.450 2.800 3.175
39 BENDING MAGNET 3 -20.000 -124.900 0.000 0.000 0.000
40 EDGE ANGLE 4 0.000 -124.900 0.450 2.800 3.175
41 DRIFT 1 20.100 0.000 0.000 0.000 0.000
ENTER A COMMAND.

```

Fig. A-7.

A display of the input TRACE file LNTRP.DAT, the short track.

```

LISTE
# TRANSPORT ELEMENTS # PARAMETERS
1 QUADRUPOLE      2   -679.200    17.600    0.000    0.000    0.000
2 DRIFT           1     53.022     0.000    0.000    0.000    0.000
3 DRIFT           1     53.286     0.000    0.000    0.000    0.000
4 QUADRUPOLE      2     722.380    17.600    0.000    0.000    0.000
5 DRIFT           1     107.360     0.000    0.000    0.000    0.000
6 QUADRUPOLE      2   -686.650    17.600    0.000    0.000    0.000
7 DRIFT           1     108.400     0.000    0.000    0.000    0.000
8 QUADRUPOLE      2     484.270    17.600    0.000    0.000    0.000
9 DRIFT           1     106.680     0.000    0.000    0.000    0.000
10 DRIFT          1      2.747     0.000    0.000    0.000    0.000
11 QUADRUPOLE     2   -106.840    17.600    0.000    0.000    0.000
12 DRIFT          1     23.900     0.000    0.000    0.000    0.000
13 DRIFT          1     42.750     0.000    0.000    0.000    0.000
14 DRIFT          1     96.283     0.000    0.000    0.000    0.000
15 QUADRUPOLE     2   -1113.200    11.200    0.000    0.000    0.000
16 DRIFT          1      38.232     0.000    0.000    0.000    0.000
17 QUADRUPOLE     2    1251.800    11.200    0.000    0.000    0.000
18 DRIFT          1     25.400     0.000    0.000    0.000    0.000
19 DRIFT          1     25.400     0.000    0.000    0.000    0.000
20 QUADRUPOLE     2     482.200    11.200    0.000    0.000    0.000
21 DRIFT          1      38.232     0.000    0.000    0.000    0.000
22 QUADRUPOLE     2   -881.720    11.200    0.000    0.000    0.000
23 DRIFT          1     96.283     0.000    0.000    0.000    0.000
24 DRIFT          1     42.750     0.000    0.000    0.000    0.000
25 DRIFT          1     20.100     0.000    0.000    0.000    0.000
ENTER A COMMAND.

```

Fig. A-8.

A display of the input TRACE file LNTRCEN.DAT for the straight-through track.

```

DSTP
# TRANSPORT ELEMENTS # PARAMETERS
1 QUADRUPOLE 2 -679.200 17.600 0.000 0.000 0.000
2 DRIFT 1 53.022 0.000 0.000 0.000 0.000
3 DRIFT 1 53.286 0.000 0.000 0.000 0.000
4 QUADRUPOLE 2 722.380 17.600 0.000 0.000 0.000
5 DRIFT 1 107.360 0.000 0.000 0.000 0.000
6 QUADRUPOLE 2 -686.650 17.600 0.000 0.000 0.000
7 DRIFT 1 108.400 0.000 0.000 0.000 0.000
8 QUADRUPOLE 2 484.270 17.600 0.000 0.000 0.000
9 DRIFT 1 106.680 0.000 0.000 0.000 0.000
10 DRIFT 1 2.747 0.000 0.000 0.000 0.000
11 QUADRUPOLE 2 -106.840 17.600 0.000 0.000 0.000
12 DRIFT 1 23.900 0.000 0.000 0.000 0.000
13 EDGE ANGLE 4 0.000 -124.900 0.450 2.800 3.175
14 BENDING MAGNET 3 -20.000 -124.900 0.000 0.000 0.000
15 EDGE ANGLE 4 -20.000 -124.900 0.450 2.800 3.175
16 DRIFT 1 43.340 0.000 0.000 0.000 0.000
17 QUADRUPOLE 2 -1157.400 11.200 0.000 0.000 0.000
18 DRIFT 1 8.800 0.000 0.000 0.000 0.000
19 QUADRUPOLE 2 989.180 11.200 0.000 0.000 0.000
20 DRIFT 1 10.000 0.000 0.000 0.000 0.000
21 EDGE ANGLE 4 20.000 860.050 0.450 2.800 3.175
22 BENDING MAGNET 3 3.000 860.050 0.000 0.000 0.000
23 EDGE ANGLE 4 -17.000 860.050 0.450 2.800 3.175
24 DRIFT 1 10.330 0.000 0.000 0.000 0.000
25 EDGE ANGLE 4 17.000 146.050 0.450 2.800 3.175
26 BENDING MAGNET 3 17.000 146.050 0.000 0.000 0.000
27 EDGE ANGLE 4 0.000 146.050 0.450 2.800 3.175
28 DRIFT 1 15.000 0.000 0.000 0.000 0.000
29 EDGE ANGLE 4 0.000 146.050 0.450 2.800 3.175
30 BENDING MAGNET 3 17.000 146.050 0.000 0.000 0.000
31 EDGE ANGLE 4 17.000 146.050 0.450 2.800 3.175
32 DRIFT 1 10.330 0.000 0.000 0.000 0.000
33 EDGE ANGLE 4 -17.000 860.050 0.450 2.800 3.175
34 BENDING MAGNET 3 3.000 860.050 0.000 0.000 0.000
35 EDGE ANGLE 4 20.000 860.050 0.450 2.800 3.175
36 DRIFT 1 10.000 0.000 0.000 0.000 0.000
37 QUADRUPOLE 2 -928.640 11.200 0.000 0.000 0.000
38 DRIFT 1 8.800 0.000 0.000 0.000 0.000
39 QUADRUPOLE 2 412.380 11.200 0.000 0.000 0.000
40 DRIFT 1 43.340 0.000 0.000 0.000 0.000
41 EDGE ANGLE 4 -20.000 -124.900 0.450 2.800 3.175
42 BENDING MAGNET 3 -20.000 -124.900 0.000 0.000 0.000
43 EDGE ANGLE 4 0.000 -124.900 0.450 2.800 3.175
44 DRIFT 1 20.100 0.000 0.000 0.000 0.000
45 DRIFT 1 0.010 0.000 0.000 0.000 0.000
ENTER A COMMAND.

```

Fig. A-9.

A display of the input TRACE file LNTRC3.DAT for the long track with 3° bends.