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TRANSPORT
AN ION OPTIC PROGRAM
LBL VERSION

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CONTENTS

Abstract 1-1
Introduction 1-1

Section 1 — Theory

Theory of Ion Optics 1-2
Matrix Method 1-2
Physical Significance of the Matrix Elements 1-7
Momentum and Energy Resolution 1-8
Phase Space Formalism on Optic Theory. 1-10
Definition of the Beam 1-13
Condition for a Waist 1-16
Physical Significance of the Elements of the Beam. 1-17
Betatron-Beam Transformations 1-21
Polygon Calculation and Beam Line Acceptance 1-22
Matrices and Vector Space 1-24
Numerical Nomenclature for Vector Space 1-26

Optimization of Variables 1-27
Variables and Vary Codes 1-31
Internal Constraint on Variables 1-32

Section 2 — Standard Data Input, Option 0

TRANSPORT Data Deck Structure 2-1
Coordinate System and Sign Configurations 2-1
Data Input Format 2-2

Option 0, The Basic Data Deck 2-3
1. Beam Ellipsoid Input 2-6
2. Bending Magnet Pole Face Rotation 2-8
3. Drift Length 2-9
4. Bending Magnet 2-10
5. Quadrupole Magnet 2-11
6. Slit 2-11
7. Axis Shift 2-12
8. Misalignment 2-12
9. Repetition 2-14
10. Constraint 2-15

11. Accelerator Energy Gain Section 2-16
12. Beam Correlation 2-17
13. Output Specification 2-17
14. Arbitrary Matrix 2-19
15. Unit Change. 2-20
16. Parameter Input. 2-22
17. Second Order 2-25
18. Sextupole Magnet 2-25
19. Solenoid Magnet 2-26
20. Beam Rotation 2-27
21. Stray Field and Miscellaneous Input. 2-28
22. Particle Vectors 2-30
23. Particle Separator 2-32
24. Plot Options 2-33
25. Calculated Matrix. 2-34
26. Space Charge 2-38
27. RF Buncher 2-39

Section 3 — Modification of Data

Options 3-1

Option 1 Data Input. 3-1
Option 2 Data Input. 3-2
Data Array and Names 3-3
Option 3 Data Input. 3-8
Option 4 3-14
Option 5 3-18

Section 4 — Interactive Transports

Teletype Input Options 4-1
ABORT 4-1
ALINE 4-1
BEAM (TRAN3) or B 4-1
CANCEL (TRAN3) or C 4-1
FIN 4-2
FORCE (TRAN4) 4-2
FORCE, I, X. 4-2
GO 4-2
LABLE (TRAN4) or L 4-2

MATRIX or MA 4-3
MDATA (TRAN3) or M 4-4
NAME or NA 4-4
NCASE 4-4
OUTPT 4-5
PDATA or PD 4-5
POLYG and POLYG, MATRIX 4-5
PRINT, LOC, LIST. (TRAN3) 4-5
PULL 4-5
RAY (TRAN3) or R 4-5
RECAL or RE 4-6
RESPN (TRAN4) 4-7
SAVE or SA. 4-7
SCALE (TRAN3) or SC 4-7
SEGMT (TRAN3), SEGMENTATION or SE 4-8
SNAPB (TRAN3) or SB 4-9
SNAPB (TRAN3) or SD 4-9
SOLVE or I 4-9
VARMIT INTERUPT 4-10
START 4-10
TABLE (TRAN4) or TA 4-11
TITLE or TI 4-11
TIME 4-11
TLOC (TRAN4). 4-11
VECT 4-11

Section 5 — Running at Lawrence Berkeley Laboratory

Availability of Berkeley Transport Code 5-1
LBL Transports 5-1
Loading at LBL 5-1
Setting Field Length 5-2
Setting Output Line Limit. 5-2
Starting a Teletype or Vista Job 5-7
Standard TRANSPORT Output 5-11
Example 1 - Optimization of Simple Quadrupole Doublet. 5-15
Example 2 - 130 MeV/c Muon Channel 5-15
Example 3 - ESCAR Ring 5-15
Example 4 - K^- Beam Line with π Contamination. 5-16
Example 5 - Astron Injection Trombone 5-16
Example 6 - Evaluation of Magnet Misalignments 5-17
Example 7 - Option 3 Chi-Square Search 5-17
Example 8 - LEP Channel Histograms 5-19
Example 9 - Pep, Long Beam Line Continued in Several Sequential Cases. 5-19

References 6-1

ABSTRACT

TRANSPORT is a computer code for calculating properties of charged particle beam transport systems using the matrix method in a six-dimensional phase space. At Berkeley we have a version of TRANSPORT translated into FORTRAN by the author from the original BALGOL SLAC TRANSPORT. We have included many addititional elements, options and procedures which are explained here along with a standard TRANSPORT user's manual. Some of the important additions are polygon transformation, ray tracing, particle separator, space charge, output plotting, interactive on-line calculations, and flexible data manipulation procedures.

INTRODUCTION

TRANSPORT is a computer code for the evaluation of charged particle beam transport systems.[1] It evaluates a given beam line by calculating the six-dimensional transformation matrix of the line in terms of its physical parameters, such as magnetic field strengths and magnet spacings. This transformation matrix may be used to transform given particle vectors along the beam line, transform a six-dimensional phase space ellipsoid along the beam line representing the particle bunch from an accelerator, or transform the various apertures encountered along the beam line to a specified location so as to evaluate the beam line acceptance and solid angle. TRANSPORT will also produce useful summary tables and graphs of the beam, vectors, acceptance polygons and phase space ellipses when directed to do so. Some of these calculations may be carried out to second order.

Often a user does not know all the parameters of his system, but knows apriori the results he desires. He may represent these results in the form of constraints on the system and designate that TRANSPORT is at the liberty to vary certain specified parameters in order to satisfy these constraints through first order. Constraints may be placed on the accumulated length, the accumulated transformation matrix elements, the beam phase space projections and tilts, the beam centroid (analogous to constraining a vector) or any given combination of the constraints.

The variables at a users command are the beam phase space dimensions, drift lengths, bending magnet fields, indices and angles of entry and exit, quadrupole lengths and fields, solenoid length and fields, phase plane rotations, and magnet misalignments and axis shifts. Combinations of these may be varied to produce the specified results.

The six dimensional beam phase space ellipsoid represents the particle bunch eminating from an accelerator. The particle distribution from a secondary production target can better be analyzed by considering the beam line phase space acceptance. TRANSPORT will calculate this acceptance and additionally can transform up to 40 particle vectors along the beam line. These vectors can be used to represent beams of several momenta (small dp/p) or beams of several particles of the same momenta such as π^- and K^- beams to be separated by particle separators. TRANSPORT will also calculated the acceptance area (solid angle) as a function of momentum so that the expected first order flux can readily be estimated, see Option 5 and polygon calculation.

Finally, TRANSPORT will allow a user to cycle any parameter or any set of up to four parameters over a given grid or randomly and evaluates the rms deviation to the specified constraints (Option 3). The result is the functional dependence of the constraints on the selected variables and is very useful in solving problems sensitive to starting conditions.

Section 1 - Theory

THEORY OF ION OPTICS

We will consider a beam transport system to be made up of a series of magnets (dipole, quadrupole, and sextuple), drift spaces, and such special elements as velocity separators, etc., through which a charged particle beam progresses. A particle source at $z = 0$, such as a cyclotron, emits individual particles along some limited range of directions. The extreme trajectories determine the beam envelope propagating in the z direction. This envelope is bent and displaced through physical space by the interaction of the particles with the fields of the magnets. To ease the problem of drawing the particle's trajectories, it is customary to straighten out the z axis, masking all deflections of the physical reference axis. This straightened z axis is referred to as the optic axis or paraxial ray, and all particle positions and directions are given as displacements from this axis and its direction in physical space. A cut in the vertical plane (y axis) from the optic axis outward is drawn, by convention, above the optic axis. A cut in the horizontal plane (x axis) from the optic axis outward is drawn below the optic axis, as shown in Fig. 1. An individual ray in the horizontal plane (dotted line in Fig 1) which passes through the optic axis ($x = 0$) is represented by a change in sign (reflection) at the point of zero passage. A waist is said to occur at the point of minimum beam dimension in either plane.

Th optic axis of a beam of particles is actually the trajectory of a particle of the desired energy ($dE = 0$) leaving the source with zero displacement (x and y) and zero emergence (x' and y'). The energy of the optic axis is unique, particles leaving the source at $z = 0$ with $x = y = x' = y' = 0$, but with energy different from that of the optic axis will be displaced from it due to dispersion effects in bending magnets. Off energy particles with nonzero x, y, x', and y' will come to a focus longitudinally displaced from the focus for the paraxial energy due to the chromatic abberations in the various focusing elements.

Matrix Method

TRANSPORT uses a matrix formalism[2] to represent a charged particle beam line made of various magnetic elements. This formalism assumes that the output vectors of an arbitrary magnetic configuration can be expanded as a power series in the initial vector elements. If we consider a six-dimensional differential vector space x, x', y, y', s, δ whose quantities are a measure of the displacements from the paraxial trajectory, then

$$
\begin{aligned}
x &= R_{11}x_0 + R_{12}x_0' + R_{13}y_0 + R_{14}y_0' + R_{15}s_0 + R_{16}\delta_0 + R_{17}x_0^2 + R_{18}x_0x_0' + \cdots \\
x' &= R_{21}x_0 + R_{22}x_0' + R_{23}y_0 + R_{24}y_0' + R_{25}s_0 + R_{26}\delta_0 + R_{27}x_0^2 + R_{28}x_0x_0' + \cdots \\
y &= R_{31}x_0 + R_{32}x_0' + R_{33}y_0 + R_{34}y_0' + R_{35}s_0 + R_{36}\delta_0 + R_{37}x_0^2 + R_{38}x_0x_0' + \cdots \\
y' &= R_{41}x_0 + R_{42}x_0' + R_{43}y_0 + R_{44}y_0' + R_{45}s_0 + R_{46}\delta_0 + R_{47}x_0^2 + R_{48}x_0x_0' + \cdots \\
s &= R_{51}x_0 + R_{52}x_0' + R_{53}y_0 + R_{54}y_0' + R_{55}s_0 + R_{56}\delta_0 + R_{57}x_0^2 + R_{58}x_0x_0' + \cdots \\
\delta &= \delta_0
\end{aligned}
$$

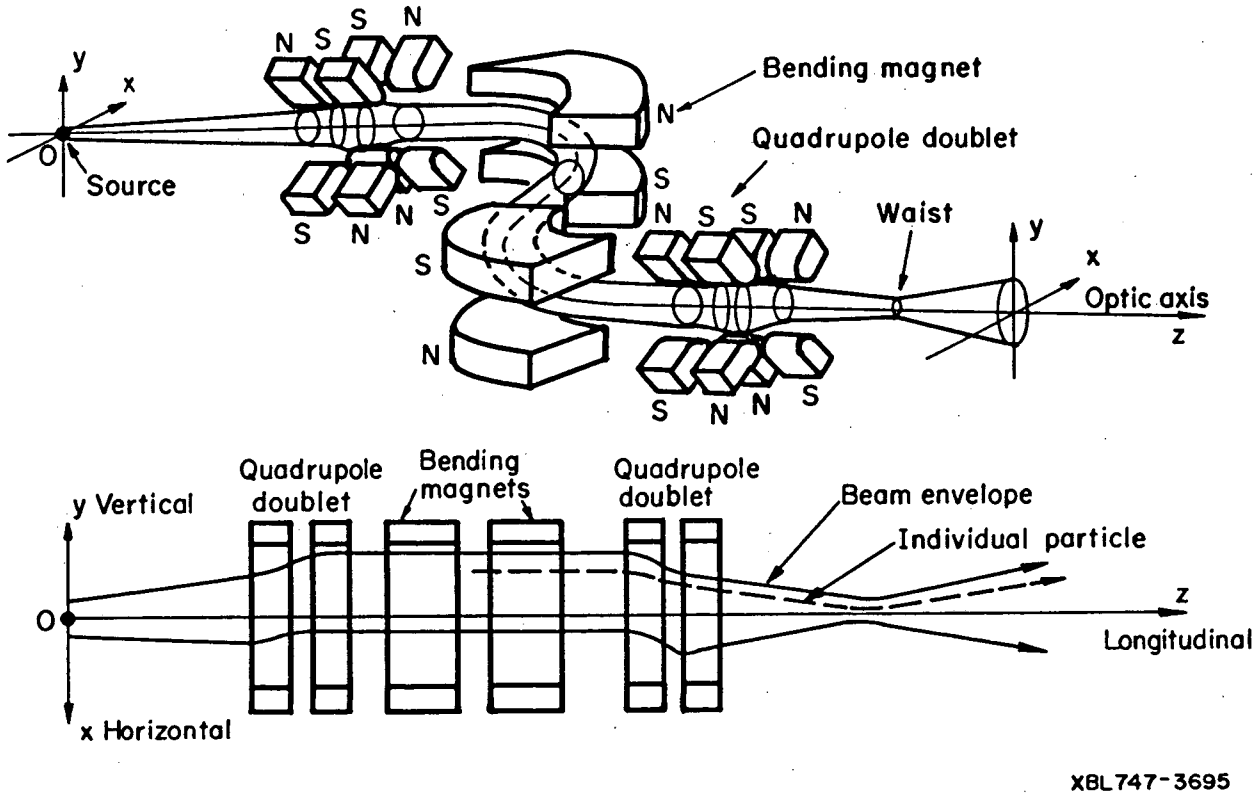

Fig. 1. Typical external beam system and its ideal representation.

where x_0, x_0', y_0, y_0', s_0, and δ_0 are the initial small deviations from the paraxial trajectory and the expansion coefficients R_{ij} are functions of the magnetic field parameters such as, current in the magnets, distance between the magnets, etc.

In a first order theory, we assume x_0, x_0', y, y_0', s_0, and δ_0 to be small so the all terms R_{NM} and higher may be neglected for M greater than 6. In the expansions of x, x', y, y' and s, the initial coordinates are considered small when x_0, y_0, s_0 are much less than the radius of curvature of the bending magnets and when x', y' expressed in radians and $\delta = dp/p$ are much less than unity. Then, the trajectory expansions may be written as:

$$V = R_1 V_1 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \\ s \\ \delta \end{bmatrix}$$

where V_1 is a particle vector and R_1 the first order transformation matrix.

When higher order terms are to be included in the expansions, the matrix formalism can still be applied by linearizing the higher order terms with the attendant increase in the dimensionality of the vector space. The theory has been extended by K. L. Brown[3] and by M. F. Tautz[4] to include third order terms in the transformation matrix. In first order, TRANSPORT works in a six-dimensional vector space x, x', y, y', s, δ. In second order, the vector space is 42-dimensional (although this could be reduced to 27 dimensions by use of the obvious symmetries) such that if V is the first order vector, then the second order vector is V + V ** 2, e.g.,

$$x, x', y, y', s, \delta, x^2, xx', xy, xy', xs, x\delta, x'x', x'^2, x'y, x'y', x's, x'\delta, yx \ldots.$$

The second order transformation matrix construction is:

$$R = \left[\begin{array}{c|c} (R_1) & \text{aberrations} \\ \hline 0 & \begin{array}{c}\text{(2nd order} \\ \text{matrix} \\ \text{elements)}\end{array} \end{array}\right]$$

where (R_1) is the 6×6 first order matrix and the second order matrix elements are the square of the first order elements, e.g.,

$$\begin{aligned} x^2 &= (R_{11}x + R_{12}x' + R_{13}y + R_{14}y' + R_{15}s + R_{16}\delta)^2 \\ &= R_{11}^2 x^2 + R_{11}R_{12}xx' + R_{11}R_{13}xy + \ldots\ldots R_{16}^2\delta^2, \text{etc.} \end{aligned}$$

So

$$R(6J + K,\ 6N + M) = R(J,N)\ R(K,M) \text{ for } \begin{cases} J = 1,6 \\ K = 1,6 \\ N = 1,6 \\ M = 1,6 \end{cases} .$$

The aberrations $R(N,M)$ are related to the second order aberration coefficients of Ref. 3, $T(ijk)$, as follows

$$R(N,\ 6J + K) = 1/2[T(N,\ J,\ K) + T(N,\ K,J)]$$
$$R(N,\ 6K + J) = R(N,\ 6J + K).$$

For a moment consider the general 6×6 matrix to be de-coupled into a horizontal bend matrix and a vertical nonbend plane matrix. The de-composition is

$$\begin{bmatrix} dx \\ dx' \\ dp/p \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{16} \\ R_{21} & R_{22} & R_{26} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x_0' \\ dp/p \end{bmatrix}$$

in the horizontal plane and

$$\begin{bmatrix} y \\ y' \end{bmatrix} = \begin{bmatrix} R_{33} & R_{34} \\ R_{43} & R_{44} \end{bmatrix} \begin{bmatrix} y_0 \\ y_0' \end{bmatrix}$$

in the vertical plane.

The transformation representing a field free region in which there are no magnetic forces is

$$\begin{bmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} .$$

This matrix translates the vector

$$\begin{bmatrix} x_0 \\ x_0' \\ dp/p \end{bmatrix}$$

L inches downstream along the z axis.

$$x = x_0 + L\, x_0'$$
$$x' = x_0' .$$

The matrix representing a bending magnet with a nonuniform field characterized by a field index n is

$$A_H = \begin{bmatrix} \cos(1-n)^{1/2}\alpha & R(1-n)^{1/2}\sin(1-n)^{1/2}\alpha & \frac{R}{1-n}[1-\cos(1-n)^{1/2}\alpha] \\ -\frac{(1-n)^{1/2}}{R}\sin(1-n)^{1/2}\alpha & \cos(1-n)^{1/2}\alpha & (1-n)^{-1/2}\sin(1-n)^{1/2}\alpha \\ 0 & 0 & 1 \end{bmatrix}$$

in the bending plane and by

$$A_V = \begin{bmatrix} \cos n^{1/2}\alpha & Rn^{-1/2}\sin n^{1/2}\alpha \\ -\frac{n^{1/2}}{R}\sin n^{1/2}\alpha & \cos n^{1/2}\alpha \end{bmatrix}$$

in the nonbending plane. Here $n = -(dB/B)/(dR/R)$, α is the angle of bend and R is the radius of curvature of the particle in the given field.

Say the bending is in the horizontal plane; then a horizontal component to the field exists, should the particles enter or exit the magnet at an angle of other than 90 degrees. This horizontal component, B_x, produces a vertical focusing force. Also, the path length in the magnet is changed depending on which side of the optic axis the particles are located, producing a horizontal focusing.

These forces are characterized by the following focusing matrices for non-normal entry and exit.

$$A_{entrance} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{\tan\beta_1}{R} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$A_{exit} = \begin{bmatrix} 1 & 0 & 0 \\ \frac{\tan\beta_2}{R} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Here β_1 and β_2 are the angles between the normal to the pole face and the direction of propagation.

A quadrupole magnet has matrix elements given by

$$A_c = \begin{bmatrix} \cos KL & \frac{1}{K}\sin KL \\ -K\sin KL & \cos KL \end{bmatrix}$$

$$A_d = \begin{bmatrix} \cosh KL & \frac{1}{K}\sinh KL \\ K\sinh KL & \cosh KL \end{bmatrix}$$

where

$$K = \sqrt{\frac{1}{B\rho}\frac{dB}{da}} \quad .$$

$B\rho$ is the magnetic rigidity of the particles, dB/da the gradient, and L the length of the lens. The A_c matrix represents the convergent plane in that a beam entering the magnet parallel to the optic axis leaves the lens converging to a focus some distance beyond the lens exit. A_d represents the other plane, where this parallel beam leaves the lens diverging from the optic axis. Focusing in both planes can be achieved by alternating the polarity of several lenses.

A divergent second lens does not destroy the focusing produced by the first lens. This is so because the magnetic forces are proportional to the displacement from the optic axis, so that divergent force is less than the convergent force. The opposite is true in the plane where the second lens is convergent. Here the beam displacement has increased by the defocusing of the first lens so that the converging force of the second lens is even stronger.

Physical Significance of the Matrix Elements

A focus is a location where the displacement from the optic axis is independent of the angle of emergence from the source. Since

$$x = R_{11}x_0 + R_{12}x_0' .$$

This requires $R_{12} = 0$ for an arbitrary x_0'. A vertical focus is characterized by $R_{34} = 0$. In first order ray trace theory, the equations are linear, so we have the situation in which if we double the off-axis distance of the particles at the input, we double their value at the output provided we are at a focus where $R_{12} = 0$

$$x = R_{11}x_0.$$

Then the magnification is defined as x/x_0 and is therefore independent of the value of x_0 or y_0, so that;

$$\text{Horizontal Magnification} = x_{image}/x_{input} = R_{11}.$$
$$\text{Vertical Magnification} = y_{image}/y_{input} = R_{33}.$$

It is important to stress that the focus condition and magnification at the image are in terms of the matrix elements representing the physical region extending from the input to the image. The fact that the magnification in the horizontal plane is R_{11} is a result of the definition of a focus, that is, a point where the displacement is independent of the angle so that $R_{12} = 0$.

If we assume we have a mono-energetic extended source of particles, we will have an extended image at the focus as a result of the finite magnification of the system. The image size will be $x_i = R_{11}x_s$ where x_s is the size of the source. If we have a momentum spread dp/p the image size will be increased to $x_i = R_{11}x_s + R_{16}\,dp/p$. Hence the matrix element R_{16} gives the contribution to the horizontal displacement by the momentum spread of the system, i.e., it is a measure of the dispersion.

$$x_{dis} = R_{16}\,dp/p.$$

Similar physical significance can be attributed to all elements of the transformation matrix.

Momentum and Energy Resolution

The energy resolution of a system is defined as the energy spread dE in a beam of energy E such that particles whose energy is outside the range $E \pm dE/2$ will not be transmitted and particles whose energy is within this range will be transmitted. Consider the beam spot for a finite size source of particles with $dE = 0$, Fig. 2a. A group of particles with dE larger energy than this beam will be horizontally displaced due to the dispersion of the system introduced by bending magnets, (Fig. 2b). The amount of displacement is $R_{16}\ dp/p$. If a slit system of $2R_{11}x_0$ width is located here, the maximum energy spread that can get through the system is determined by the condition that $R_{16}\ dp/p$ is equal to $2R_{11}x_0$. Particles with dp/p larger than this value do not get through the system. $2R_{11}x_0$ is the full beam size for $dp/p = 0$.

$$\left(\frac{dp}{p}\right)_{res} = \frac{2R_{11}x_0}{R_{16}} .$$

The full energy spread in the beam is

$$\Delta E_{res} = \frac{8R_{11}x_0}{R_{16}} E .$$

However, a beam may have a non-uniform particle distribution with momentum so that a more meaningful definition of the resolution would be the full width at 1/2 maximum transmission.

$$\left(\frac{dp}{p}\right)_{FWHM} \leq 2\frac{R_{11}x_0}{R_{16}}$$

and the full energy spread in the beam for 100% transmission of the central momentum ($dp/p = 0$) and less than 1/2 maximum transmission of particles with $dp/p \leq (dp/p)_{FWHM}$ is given by

$$\Delta E_{res} \leq 4R_{11}x_0 E R_{16}^{-1} .$$

The resolution is a property of a given magnet system. It is independent of the particle input vector or phase space ellipse and is determined solely by the matrix elements of the transformation. For example, if a 2% energy spread is inherent in a beam incident upon a system that has a resolution of 0.5%, then a beam reaches the target for which there has been 100% transmission of particles with $dE = 0$, 50% or more transmission of particles with $dE \leq 0.5\%$, and very little transmission of particles with $dE \geq 1\%$. If one chooses to narrow the momentum defining slits in the system, he does not improve the resolution of the system but he may reduce somewhat the energy spread of the beam reaching the target at the expense of particle intensity for particles with $dE = 0$. He may not, however, reduce the energy spread indefinitely by a sufficient reduction in slit width. This results from the presence of particles of different energies with various emergencies (angle to the z axis) so that even for an infinitesimally narrow slit a finite energy width will be transmitted. Alternatively this may be seen by projecting the phase

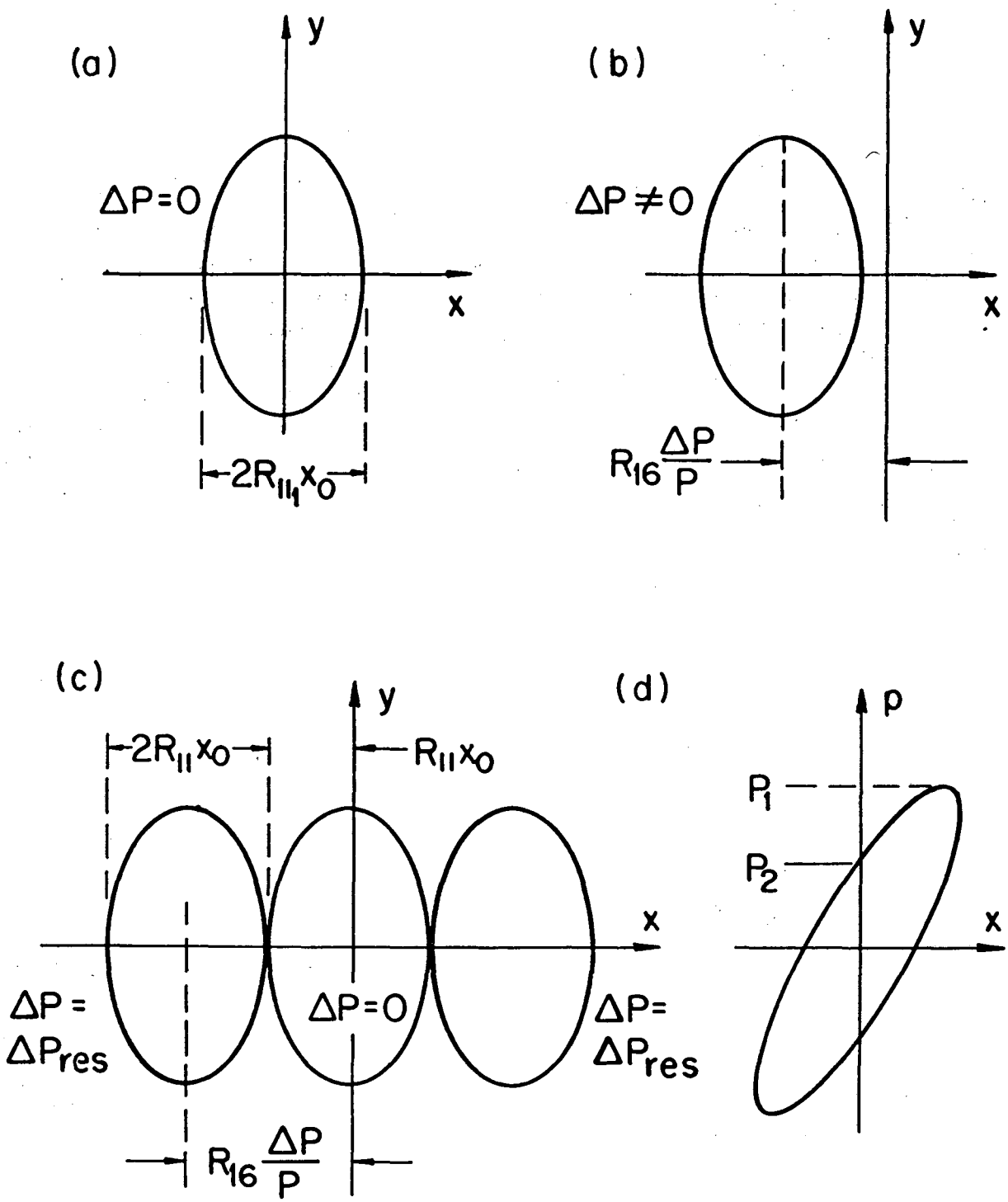

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Fig. 2. Effect of momentum spread on beam phase space and interpretation of momentum resolution in terms of the phase space ellipsoid.

ellipse of the particles onto the p-x plane (Fig. 2d). For $x \to 0$ we have a reduction in transmitted momentum spread p from p_1 to some finite irreducible minimum value p_2.

Phase Space Formalism of Ion Optic Theory

Now, with a general understanding of the matrix representation of magnetic fields we can consider the phase space formulation of beams of particles. This formalism is important since the conservation of phase area implies a relation between displacement and emergence, $A \geqslant xx'$. A single particle represented by a vector can be traced through the system by matrix multiplication; however in nature, we are not confronted with single particles, but rather groups of particles comprising a beam that we wish to transform from a source to some target restricted by specific constraints. These particles comprise a beam. If n coordinates are required to specify a given particle, then a group of particles will occupy a certain volume in n-space. If these particles comprise an internal beam of an accelerator they will be executing betatron oscillations which are independent in the axial and radial planes to first approximation. The radial differential equation is

$$\frac{d^2x}{dt^2} + \omega^2(1-n)\,x = 0$$

so that

$$x = x_m \sin(1-n)^{1/2}\,\omega t.$$

The axial differential equation is

$$\frac{d^2y}{dt^2} + \omega^2 n y = 0$$

so that

$$y = y_M \sin n^{1/2}\,\omega t.$$

The transverse momentum associated with these motions are given by $p_x = M\frac{dx}{dt}$ and $p_y = M\frac{dy}{dt}$.

$$p_x = M(1-n)^{1/2}\,\omega x_m \cos(1-n)^{1/2}\,\omega t$$

$$p_y = Mn^{1/2}\,\omega y_m \cos n^{1/2}\,\omega t.$$

The amplitude of the displacement in the radial direction is x_m while the amplitude of the corresponding momentum is $M(1-n)^{1/2}\omega x_m$. Time can be eliminated by using the properties of the trigonometric functions.

$$[\sin(1-n)^{1/2}\omega t]^2 + [\cos(1-n)^{1/2}\,\omega t]^2 = \left(\frac{x}{x_m}\right)^2 + \left(\frac{p_x}{M(1-n)^{1/2}\omega x_m}\right)^2 = 1.$$

This is the equation of an ellipse independent of time. Similarly in the vertical plane we have

$$1 = \left(\frac{y}{y_m}\right)^2 + \left(\frac{p_y}{Mn^{1/2}\omega y_m}\right)^2 .$$

If we have many particles distributed in time with the same oscillation amplitudes x_m or y_m, they will comprise an ellipse in the corresponding phase space. If we focus our attention on one single particle it will rotate around on its ellipse as time passes, confined indefinitely to its own ellipse provided phase space is conserved, i.e., the momentum (energy) is constant, etc., Fig. 3b.

In an accelerator we have present particles of many oscillation amplitudes ranging from zero up to some maximum value x_m. Considering the sum of all particles in the horizontal plane we have a two dimensional ellipsoid. Any one particle belongs to a given ellipse within this area phase ellipse, and rotates about its own ellipse with time. The particles simultaneously belong to a phase ellipse in the axial direction. In general, the particles can be described by six coordinates, and hence will lie on a six-dimensional elliptical surface within a limiting six-dimensional ellipsoid characterizing the particle distribution. The six coordinates are the particle's axial and radial displacement and momentum, and the longitudinal displacement and momentum.

The conservation of phase space guarantees that the volume or area of the ellipse remains constant during the motion while the linearity of the first order theory ensures that the distribution remains ellipsoidal. Consequently, the motion of a "beam" through magnetic systems can be described by the transformation of the particle's phase ellipse. This motion rotates and stretches the phase ellipse subject to the condition that its area or volume remains constant. The actual extent of the particles observed in the physical world is the projection of this ellipse onto the coordinate axis.

In calculating the particle distribution as it progresses through space after extraction from an accelerator, it is convenient to change the units of the phase ellipsoid. Note that in accordance to the first order theory the angles of emergence of the beam are small so that

$$p_x = p_z \sin x' \approx p_z x'$$

$$p_y = p_z \sin y' \approx p_z y'$$

p_z is the momentum of the particle in the z direction, the direction of motion. The volume of phase space of an upright ellipse whose semi-axis coincides with the coordinate system is

$$V = \frac{16}{3}\pi (x_0 x_0' \; y_0 y_0' \; z p_z^3).$$

And the area projection onto one pair of coordinate axes is

$$A_x \approx \pi x x'$$
$$A_y \approx \pi y y'$$
$$A_z \approx \pi z p_z .$$

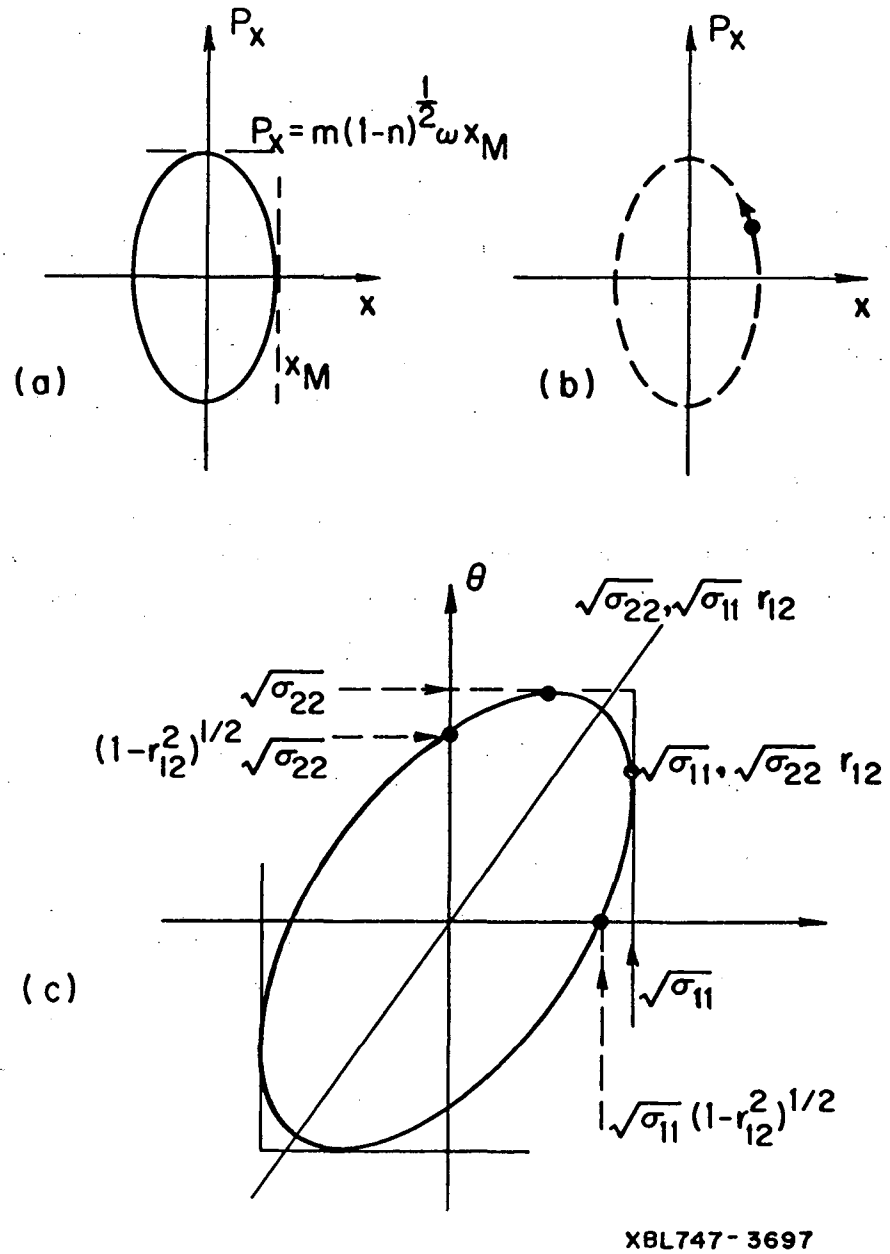


Fig. 3. a,b) Simple harmonic oscillation phase plane motion typical for simple magnets encountered in beam lines.
c) Interpretation of ellipse projections and TRANSPORT beam correlations r_{12} in the horizontal phase plane.

The constant of proportionality is the momentum p_z which is constant as long as the energy is not changed. The equation of the phase ellipse in the principal coordinate system is

$$\left(\frac{x}{x_0}\right)^2 + \left(\frac{x'}{x_0'}\right)^2 + \left(\frac{y}{y_0}\right)^2 + \left(\frac{y'}{y_0'}\right)^2 + \ldots = 1.$$

The coefficients $1/x_0^2$, etc., characterize the particle's distribution. This equation can be written in matrix form as

$$(x, x', y, y', \ldots) \begin{bmatrix} \frac{1}{x_0^2} & 0 & 0 & \cdots & \cdots \\ 0 & \frac{1}{x_0'^2} & 0 & & \\ 0 & 0 & \frac{1}{y_0'^2} & & \\ \vdots & & & \frac{1}{y_0'^2} & \\ & & & & \ddots \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \\ \vdots \end{bmatrix} = 1.$$

The reciprocal form of the coefficients $(1/x_0^2)$ suggest that we define a matrix σ^{-1} as

$$\sigma^{-1} = \begin{bmatrix} \frac{1}{x_0^2} & 0 & \cdots & & \\ 0 & \frac{1}{x_0'^2} & & & \\ \vdots & & \frac{1}{y_0^2} & & \\ & & & \frac{1}{y_0'^2} & \\ & & & & \ddots \end{bmatrix}$$

then

$$\sigma = \begin{bmatrix} x_0^2 & 0 & \cdots & & \\ 0 & x_0'^2 & & & \\ \vdots & & y_0^2 & & \\ & & & y_0'^2 & \\ & & & & \ddots \end{bmatrix}.$$

The matrix σ is called the "beam matrix", or simply the beam.

Definition of the Beam

We have shown that the particle distribution is an n-dimensional ellipsoid and we have written this as

$$a_{11} x^2 + a_{22} x'^2 + a_{33} y^2 + \ldots = 1.$$

This is the equation in the principal coordinate system. If the coordinates are rotated, we have the case shown in Fig. 3c. Here the equation for the ellipse will involve various off-diagonal terms, such as xx'. For example, in two dimensions we would have

$$a_{11}x^2 - a_{12}xx' - a_{21}x'x + a_{22}x'^2 = 1.$$

The cross terms give the measure of the rotation of the ellipse.

In n dimensions, the equation of a tilted ellipse is

$$\sum_i^n \sum_j^n a_{ij} x_i x_j = 1.$$

We can define the matrix of the coefficients a_{ij} as describing the ellipsoid and consequently, defining the particle distribution. This beam matrix is written as

$$\sigma^{-1} = \begin{bmatrix} a_{11} & a_{12} & \cdots\cdots \\ a_{21} & a_{22} & \\ \vdots & & \end{bmatrix}$$

or

$$\sigma^{-1} = a_{ij} .$$

A single particle described by a vector V transforms through a magnetic system described by a matrix R as

$$V_1 = RV.$$

The ellipsoid character of these particles can be written as

$$V^T \sigma^{-1} V = 1$$

as can be seen by the following:

$$(x, x', \delta) \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x \\ x' \\ \delta \end{bmatrix} = 1$$

and if the cross terms a_{ij} $(i \neq j)$ vanish (the ellipse is then upright) and we have

$$a_{11}x^2 + a_{22}x'^2 + a_{33}\delta^2 = 1.$$

The transformation of the ellipsoid through a magnetic system characterized by the transformation matrix R then gives the transformation of the particle distribution. Noting that $R^{-1} R = 1$, then the ellipsoid $V^T \sigma^{-1} V = 1$ can be written:

$$V^T (R^{-1}R)^T \sigma^{-1} (R^{-1}R) V = 1$$
$$(V^T R^T) R^{T-1} \sigma^{-1} R^{-1} (RV) = 1$$
$$(RV)^T (R\sigma R^T)^{-1} (RV) = 1.$$

Where we have used the fact that the reciprocation of a matrix product requires reversal of the order of factors:

$$A B = C$$
$$B^{-1} A^{-1} A B C^{-1} = B^{-1} A^{-1} C C^{-1}$$
$$B^{-1} A^{-1} = C^{-1}$$
$$(AB)^{-1} = C^{-1}$$

and the fact that taking the transpose of the product of two matrices is obtained by taking the product of the transposed matrices in reverse order

$$(R^{-1}R)^T = R^T R^{T-1}.$$

Therefore

$$V^T R^T = (RV)^T.$$

Defining the vector after transformation as $V_1 = RV$, we obtain

$$V_1^T \sigma_1^{-1} V_1 = 1$$

where

$$\sigma_1^{-1} = (R\sigma R^T)^{-1} .$$

That is to say, the ellipsoid after the transformation is a relation between the transposed particle vectors which comprise the distribution and the beam σ_1 characterizing the coefficients of the phase space ellipsoid.

σ_1 has been defined from above as

$$\sigma_1 = R\sigma R^T$$

In other words, given the beam σ at the entrance of the magnetic system and the transformation matrix of the system, the "beam" σ_1 at the output can be calculated from the above expression. The first order beam is in general defined as:

$$\sigma_1 = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} & \sigma_{14} & \sigma_{15} & \sigma_{16} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} & \sigma_{24} & \sigma_{25} & \sigma_{26} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} & \sigma_{34} & \sigma_{35} & \sigma_{36} \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} & \sigma_{45} & \sigma_{46} \\ \sigma_{51} & \sigma_{52} & \sigma_{53} & \sigma_{54} & \sigma_{55} & \sigma_{56} \\ \sigma_{61} & \sigma_{62} & \sigma_{63} & \sigma_{64} & \sigma_{65} & \sigma_{66} \end{bmatrix}$$

Condition for a Waist

Now consider the distinction between a matrix representing a waist condition and a matrix representing a focus condition. A focus matrix is defined as a transformation matrix with $R_{12} = 0$, so that $x = R_{11}\, x_0$. A transformation matrix representing a waist transforms a beam so that $\sigma_{12} = \sigma_{21} = 0$. The transformation of an upright phase ellipse by a matrix representing a focus is given by

$$\sigma_1 = \begin{pmatrix} R_{11} & 0 \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} x_0^{\,2} & 0 \\ 0 & x_0'^{\,2} \end{pmatrix} \begin{pmatrix} R_{11} & R_{21} \\ 0 & R_{22} \end{pmatrix}$$

$$\sigma_1 = \begin{pmatrix} R_{11} & 0 \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} R_{11}\, x_0^{\,2} & R_{21}\, x_0^{\,2} \\ 0 & R_{22}\, x_0'^{\,2} \end{pmatrix}$$

$$\sigma_1 = \begin{pmatrix} R_{11}\, x_0^{\,2} & R_{11} R_{21}\, x_0^{\,2} \\ R_{21}\, R_{11}\, x_0^{\,2} & R_{21}^{\,2}\, x_0^{\,2} + R_{22}^{\,2}\, x_0'^{\,2} \end{pmatrix}.$$

For a finite x_0 we have σ_1 non-diagonal, hence by definition not representing a waist. In order to have a waist we would need $\sigma_{12} = \sigma_{21} = 0$, i.e.,

$$R_{11}\, R_{21}\, x_0^{\,2} = 0.$$

For a matrix with non-zero R_{12}, we would have

$$\sigma_1 = \begin{bmatrix} R_{11}\, R_{11}\, x_0^{\,2} + R_{12}\, x_0'^{\,2} & R_{21}\, R_{11}\, x_0^{\,2} + R_{12}\, R_{22}\, x_0'^{\,2} \\ R_{21}\, R_{11}\, x_0^{\,2} + R_{22}\, R_{12}\, x_0'^{\,2} & R_{21}\, R_{21}\, x_0^{\,2} + R_{22}^{\,2}\, x_0'^{\,2} \end{bmatrix}.$$

The general requirement for a waist is

$$R_{21}\, R_{11}\, x_0^{\,2} + R_{12}\, R_{22}\, x_0'^{\,2} = 0.$$

For a non-zero R_{11}, R_{22} and a finite x_0^2 and $x_0'^2$, a sufficient and necessary requirement on the transformation matrix in order to satisfy the condition that a waist be present is

$$\frac{R_{12}\,R_{22}}{R_{21}\,R_{11}} = -\left(\frac{x_0}{x_0'}\right)^2 .$$

Note that for a point source ($x_0 = 0$) the focus matrix would be identical to a matrix representing a waist transformation. For a finite source size the two transformations are distinct.

Physical Significance of the Elements of the Beam

Physical significance can be given to the elements of the beam as they have been defined here. Consider an arbitrary ellipse defined by the beam

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} .$$

We have already shown that this can be written as

$$x^2\,\sigma_{22} - 2x\,x'\,\sigma_{12} + x'^2\sigma_{11} = \sigma_{11}\sigma_{22} - \sigma_{12}^2 .$$

This is the equation of an ellipse rotated from the coordinate axis. If σ_{12} is zero, the ellipse is upright; if σ_{12} is non-zero, then it is a measure of the tilt of the ellipse.

To picture the ellipse we must know the values of its intersection points with the coordinate axis and the values of the intersection points with its projection rectangle, Fig. 3c. To find the intersection points with the coordinate axis, we take $x = 0$ so that

$$x'^2\,\sigma_{11} = \sigma_{22}\,\sigma_{11} - \sigma_{12}^2$$

$$x' \equiv \left[\sigma_{22} - \frac{\sigma_{12}^2}{\sigma_{11}}\right]^{1/2} .$$

Defining

$$r_{12} = \frac{\sigma_{12}}{\sqrt{\sigma_{11}\,\sigma_{22}}}$$

as the correlation coefficient, we obtain

$$x' = \sqrt{\sigma_{22}}\,(1 - r_{12}^2)^{1/2} .$$

This is the point of intersection of the ellipse with the x' axis. If we take $x' = 0$, we find

$$x^2\sigma_{22} = \sigma_{22}\,\sigma_{11} - \sigma_{12}^{\;2}$$

$$x = \left[\sigma_{11} - \frac{\sigma_{21}^{\;2}}{\sigma_{22}}\right]^{1/2}$$

or

$$x = \sigma_{11}^{\;1/2}\,(1 - r_{12}^{\;2})^{1/2} .$$

This is the point of intersection with the x axis.

To find the intersection points of the ellipse with its projection rectangle we note that the slope is a maximum or minimum. Thus, differentiating the equation of the ellipse

$$x^2\sigma_{22} - 2\sigma_{12}x'x + x'^2\sigma_{11} = \sigma_{11}\sigma_{22} - \sigma_{12}^{\;2}$$

$$2x\,dx\,\sigma_{22} - 2\sigma_{12}x'\,dx - 2\sigma_{12}x\,dx' + 2x'\,\sigma_{11}\,dx' = 0$$

$$\frac{dx'}{dx}\,(2x'\,\sigma_{11} - 2\sigma_{12}x) + 2x\sigma_{22} - 2\sigma_{12}x' = 0.$$

At the tangent point we have $dx'/dx = 0$ so that

$$\frac{x}{x'} = \frac{\sigma_{12}}{\sigma_{22}} .$$

Therefore $x = \frac{\sigma_{12}}{\sigma_{22}}\,x'$. When this is substituted into the ellipse equation we obtain

$$x' = \sqrt{\sigma_{22}} .$$

So the coordinate of the intersection point is

$$x = \frac{\sigma_{12}}{\sqrt{\sigma_{22}}} = r_{12}\sqrt{\sigma_{11}} \;;\; x' = \sqrt{\sigma_{22}} .$$

Similarly, at the other tangent point we have $dx/dx' = 0$ so that

$$\frac{x'}{x} = \frac{\sigma_{12}}{\sigma_{11}} .$$

Therefore, $x' = \frac{\sigma_{12}}{\sigma_{11}}\,x$, when this is substituted into the ellipse equation we obtain

$$x = \sqrt{\sigma_{11}} \;;\; x' = \frac{\sigma_{12}}{\sqrt{\sigma_{11}}} = r_{12}\sqrt{\sigma_{22}} .$$

The physically measurable coordinate projections are $x = \sqrt{\sigma_{11}}$ and $x' = \sqrt{\sigma_{22}}$.

These are the square root of the diagonal beam matrix elements. Figure 3c shows the geometric points of the phase ellipse in terms of the matrix elements. Program TRANSPORT prints as output the following beam matrix:

$$
\begin{array}{llllll}
\sqrt{\sigma_{11}} & & & & & \\
\sqrt{\sigma_{21}} & r_{21} & & & & \\
\sqrt{\sigma_{33}} & r_{31} & r_{32} & & & \\
\sqrt{\sigma_{44}} & r_{41} & r_{42} & r_{43} & & \\
\sqrt{\sigma_{55}} & r_{51} & r_{52} & r_{53} & r_{54} & \\
\sqrt{\sigma_{66}} & r_{61} & r_{62} & r_{63} & r_{64} & r_{65}\,.
\end{array}
$$

Since $\sigma_{ij} = \sigma_{ji}$. we have $r_{ij} = r_{ji}$. The second order beam matrix σ is given in terms of the initial first order σ matrix elements as:

$$\sigma(J,K) = \sigma\left(\frac{J}{7},\frac{J}{7}\right)\sigma\left(\frac{K}{7},\frac{K}{7}\right)\left[1 + 2\,\delta(J = K)\right] \qquad \text{for} \quad \left\{\begin{array}{l} J=7,14,21,28,35,42 \\ K=7,14,21,28,35,42 \end{array}\right. .$$

Explicitly, the second order vector space is as follows:

Vector element number	Vector parameter	Initial value	Vector element number	Vector parameter	Initial value
1	X	0	25	Y'X	σ_{41}
2	X'	0	26	Y'X	σ_{42}
3	Y	0	27	Y'Y	σ_{43}
4	Y'	0	28	Y'Y'	σ_{44}
5	S	0	29	Y'S	σ_{45}
6	δ	0	30	Y'δ	σ_{46}
7	X^2	σ_{11}	31	SX	σ_{51}
8	XX'	σ_{12}	32	SX'	σ_{52}
9	XY	σ_{13}	33	SY	σ_{53}
10	XY'	σ_{14}	34	SY'	σ_{54}
11	XS	σ_{15}	35	SS	σ_{55}
12	Xδ	σ_{16}	36	Sδ	σ_{56}
13	X'X	σ_{21}	37	δX	σ_{61}
14	X'^2	σ_{22}	38	δX'	σ_{62}
15	X'Y	σ_{23}	39	δY	σ_{63}
16	X'Y'	σ_{24}	40	δY'	σ_{64}
17	X'S	σ_{25}	41	δS	σ_{65}
18	X'δ	σ_{26}	42	δ^2	σ_{66}
19	YX	σ_{31}			
20	YX'	σ_{32}			
21	YY	σ_{33}			
22	YY'	σ_{34}			
23	YS	σ_{35}			
24	Yδ	σ_{36}			

Where the σ_{JK} are the first order 6×6 matrix elements.

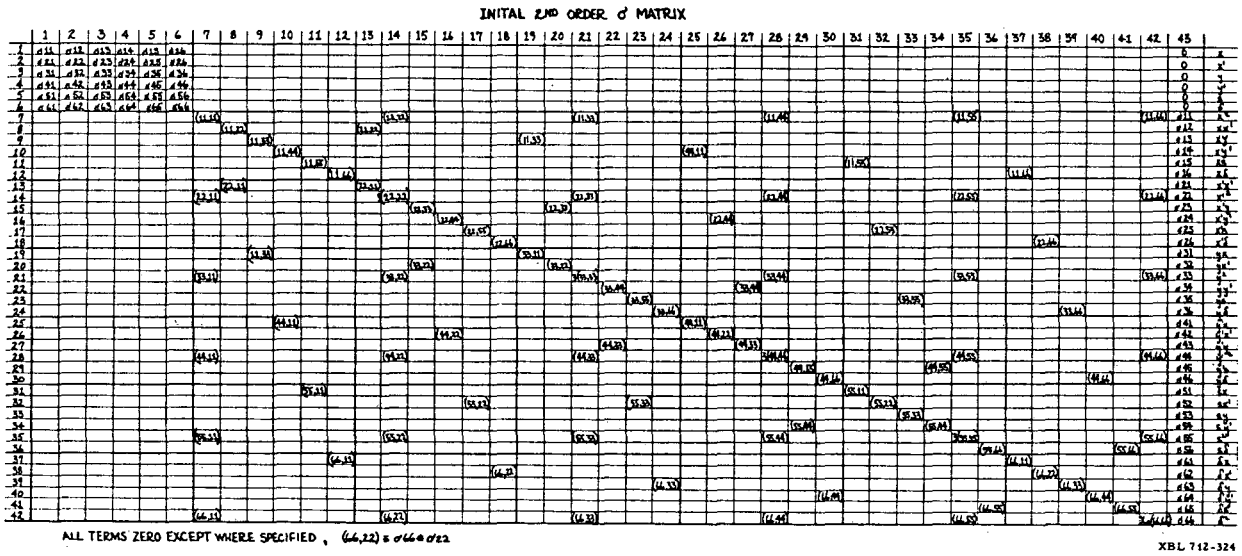


Fig. 4. Construction of the second order TRANSPORT beam matrix. All terms not explicity given are zero.

The σ-matrix has by mathematical construction an elliptical boundary on any plane on which it is projected. When second order calculations are performed the σ-matrix takes on the interpretation of a circumscribed ellipsoid containing the real nonlinear phase space. The actual nonlinear transformations will be performed by TRANSPORT whereever a plot card (24. ijkl.) is used to generate plots. In this calculation the second order accumulated matrix (RC-matrix) is used to transform 36 boundary points on the initial projected phase space and these are shown as points (.) on the plot. The circumscribed ellipsoid is also plotted by (x) and may be considerably larger than the actual phase space due to the distortions introduced by the nonlinearities.

Betatron–Beam Transformations

The betatron functions introduced by Courant and Snyder[5] have meanings completely analogous to the elements of the σ-matrix used by TRANSPORT. In a two-dimentional phase space of area πE, the betatron function α, β, and γ are related to the σ-matrix as

$$\sigma = E\begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

so that

$$\sigma_{22} = \gamma E$$
$$\sigma_{11} = \beta E$$
$$\sigma_{12} = -\alpha E$$

where $\sigma_{12} = r_{12}\sqrt{\sigma_{11}\sigma_{22}}$, r_{12} being the beam correlation coefficient and E is the phase area divided by π. Betatron functions can be introduced as input to TRANSPORT by proceeding the beam card by a 21.0. card giving the radial and vertical phase areas E_x and E_y. These areas can be calculated from the σ-matrix as follows

$$\beta\gamma - \alpha^2 = 1$$
$$\sigma_{11}\,\sigma_{22} = E^2\beta\gamma$$
$$\sigma_{12}\,\sigma_{21} = E^2\alpha^2$$

so that

$$E^2 = \sigma_{11}\,\sigma_{22} - \sigma_{12}\,\sigma_{21} = \det\sigma.$$

TRANSPORT will also allow constraints to be placed upon the betatron functions and will generate a table of the α, β, γ's as described elsewhere in this report.

Polygon Calculation and Beam Line Acceptance

The beam line transmission is determined by how well the acceptance of the beam line is matched to the emittance of the particle source. TRANSPORT will calculate the enclosed polygon in the horizontal and vertical phase space determined by the apertures encountered along the beam line. Physically, only particles which are within this polygon will successfully negotiate the apertures of the beam line and therefore be transmitted. If a target is included in the data (24.1. Data Entry) the solid angle acceptance will also be calculated. Plots of the beam acceptance showing the polygon, beam ellipsoid and particle vectors can also be made.

Aperture information is processed at the beginning and end of each quadrupole, particle separator, and sextupole and at the location of slits designated by a 6. or 16.4. and 16.5. data card. Aperture information may be specified for bending magnets, drift spaces and solenoids by using the slit options which designate apertures for succeeding beam elements possessing length. When the 16.4.H. and 16.5.V. aperture cards are used they will specify apertures for all succeeding bending magnets. These apertures are transformed backwards in the phase space under the assumption of decoupling of the phase planes. This restricts the aperture calculation to beam lines which do not contain solenoids, misaligned quadrupoles or other elements which mix the horizontal and vertical planes. Circular apertures are approximated by square apertures in the polygon calculation. In order to account for the reduction of the quadrupole apertures by beam plumbing a fractional fillage can be specified by the 16.[16.X. data card where X] is the length of the circumscribed square leg divided by the quadrupole diameter.

The polygon calculation is initiated by Option 5. The calculation begins at the location of the 13.5. data card which specified the location where all apertures will be transformed. This card may be placed anywhere along the beam line, though generally it is particularly meaningfull when placed at the location of the particle source. The table of verticies of the enclosed polygon, polygon area and plot of the polygon and beam are printed at each location where a 13.6. Data Card appears.

The vertices of the enclosed polygon are tagged as to which apertures intersect at that vertex.

$$TAG = TYPE + I/1000$$

e.g., a bending magnet (Type 4) which is the 62 element in the beam line (I value 62) has a tag = 4.062. The I value for each type is printed at the beginning of each data calculation along with the data set. Each vertex is also tagged with the name of the aperture which lies counterclockwise from the vertex as shown in Fig. 5. The vertices are also ordered counter clockwise.

The phase space coordinates of the vertex are also given and may be interpreted with the aid of Fig. 5 for the Jth vertex. The solid angle acceptance for a finite target may be calculated in addition to the beam line acceptance by use of the 24.1. data option specifying the phase space size of the target assumed centered on the paraxial trajectory. The solid angle and average angular acceptance is then calculated by finding the areal overlap of the target and beam line acceptance polygon A_0 divided by the target size W.

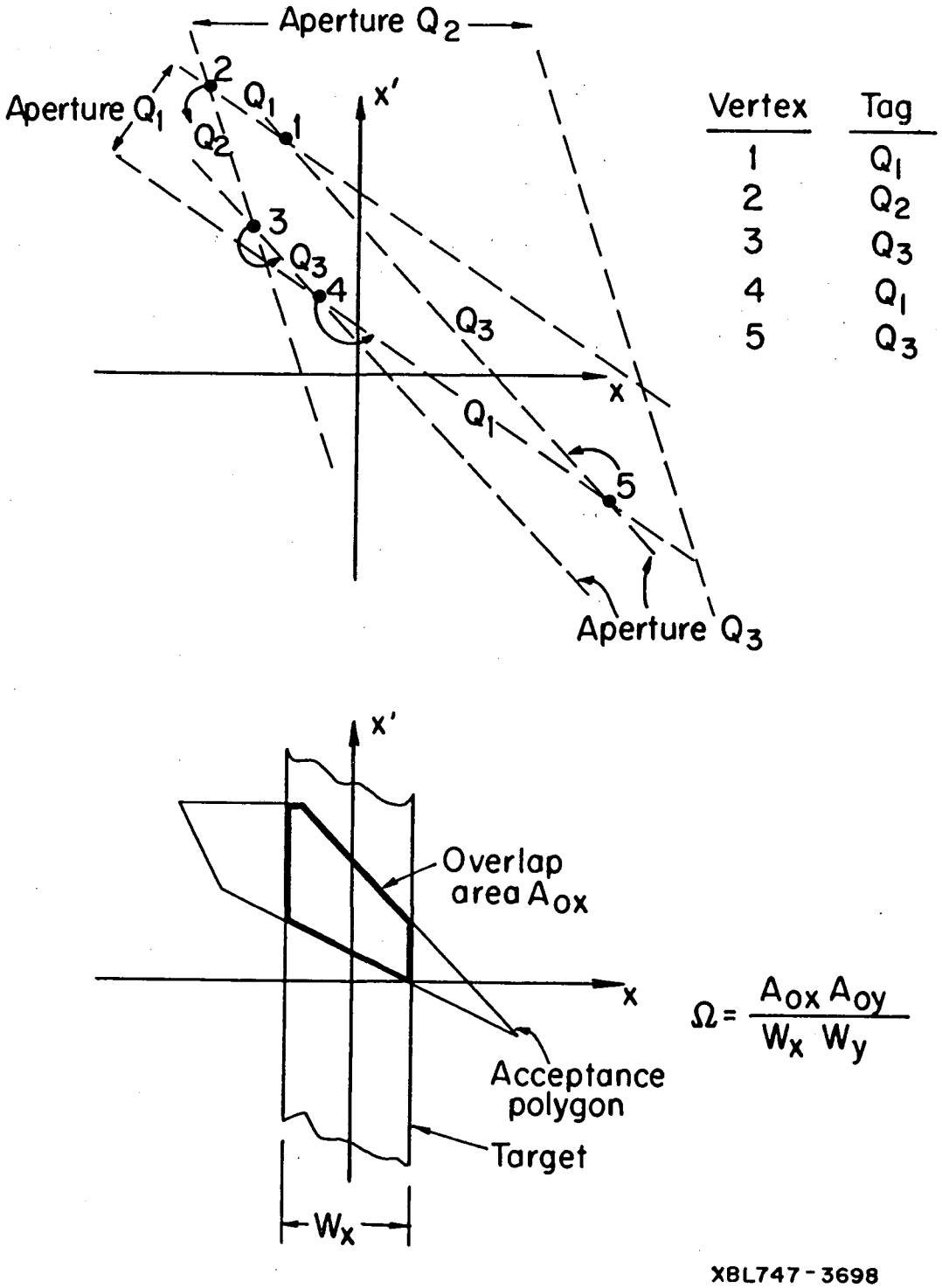


Fig. 5. Generation of an enclosed polygon from magnet apertures and the definition of solid angle acceptance Ω for a target of width W_x.

$$\Omega = \frac{A_{ox} A_{oy}}{W_x W_y} .$$

Figure 5 shows the target and polygon overlap for solid angle calculations.

Often one wishes to perform the acceptance calculation at several different momenta since the polygon area and shape are dependent on the beam momentum. This is facilitated by using the 13.7. data card in place of the 13. 6. data card. Now the polygon transformation will be performed at each momentum specified by the 24.4. card and will include the effect of dispersion and chromatic aberrations. The result of such a calculation is the determination of the first order momentum acceptance of the beam line.

The apertures can optionally be transformed to the location of the 13. 6. or 13. 7. card by selection of the 13. 30. option. The polygon area is the same as at the 13. 5. location. The 13. 29. option will suppress the output from the 13. 5. location.

When the aperture calculation is being done, the horizontal and vertical polygon acceptance will be tabulated in the horizontal and vertical position of the first vector in the A–table and will be plotted on the beamline plot if the first vector is to be plotted on this plot. The acceptance polygon areas will also be printed after each element possessing an aperture so that the reduction in phase space acceptance can be evaluated for each element of the beam line.

If the names of various data elements appear on the sentinel card of the Option O data deck these element will not be used in the calculation of the acceptance polygons. The elements will still be in the beam line and will contribute to the transformation matrix, however, their apertures will be considered non-apertures and will not be transformed into the acceptance polygons. This feature allows the assessment of the removal of apertures from a given beam line to find the improvement obtained by removal of that aperture. Example:

73. 0. Q1 Q2 Q3 SLIT4 BM2 SLIN

will exclude the elements named, i.e., Q1, Q2, Q3, SLIT4, BM2, and SLIN will not contribute apertures to the polygon. The names must begin as the third entry on the sentinel card and be all on this one card.

Matrices and Vector Space

TRANSPORT uses two distinct types of matrices, one to represent the beam of particles. (SI or σ matrix) and the second to transform this beam along the beam line. Of the second type, five different matrices are used as defined in Table I below.

Table 1.

External name	Internal name	Print command	Point of origin	Use
R-TRANSFORM	R	13. 8.	Preceding element	Transformation matrix for individual element.
TRANSFORM-1	RC	13. 4.	Last update[a]	Accumulated transformation matrix from last update, may be constrained.
TRANSFORM-2	RC2	13. 24.	6.0.2 data card	Accumulated transformation matrix, never updated, may be constrained.
TRANSFORM 1 FROM BEGINNING	R3	13. 4.	Start of Beamline	Total transformation matrix.
POLYGON-MATRIX	RTN	13. 45.	13. 5. data card	Transformation of apertures, used in Polygon calculation.
NONE	SI	---	Start of beamline and transformed to each update.[a]	Beam ellipsoid matrix; this matrix may be constrained.
NONE	C1	13.1.	Last update[a]	Transformed beam matrix $C_1 = R_c S_I R_c^T$

[a]The elements initiating an update of the beam (Re-initializing RC matrix and subsequently translating the SI matrix) are 1.-, 12.-, 6.0.1., 7,-, 8.-, 10.I.j. ($7 \geq I \geq J > 0$), 16.2.DE., and the 17. element.

The interpretation of these matrices and their definitions will be given below. The main distinction between the various transformation matrices is their point of origin and the effect of the various redefinition cards which update (redefine) their point of origin.

An "update of the beam" is produced by any data card with type code 1-, 12-, 6.0.1., 7-, 8-, 10.I.j. ($7 \geq I \geq J > 0$), 16.2., and 17-. This "update" transforms the beam matrix and sets a flag such that the next transformation will re-initialize the accumulated transformation matrix, R_c, i.e.,

$$\sigma = R_c \sigma_0 R_c^T$$

and then initialize the R_c – matrix

$$R_c = R.$$

Here σ_0 is the beam matrix before the update and σ is the updated beam matrix. R is the matrix for the next element in the beam line.

R-Matrix. The R-Matrix is the transformation matrix for a single element of the beam line. This matrix is 6×6 in first order and 42×42 in second order and may be printed in the output stream by use of the 13. 8. or the 13. 48. output card.

RC-Matrix. The RC Matrix is the accumulated transformation matrix from the last beam update. Beam updates are produced by any constraint on the beam via the appropriate 10. card, or any of the following type cards 1., 7., 8., or A 6. 0. 1. card. The RC-Matrix is 6×6 in first order and 42×42 in second order. This matrix may be printed in the output stream by a 13. 4. or 13. 42. card.

RC2-Matrix. The RC2-Matrix is the accumulated matrix from the point of its definition given by the occurrence of a 6. 0. 2. data card. This matrix is never updated except by redefining its origin by a 6. 0. 2. card. The RC2 Matrix can be constrained and is 6×6.

R3 Matrix. The R3 Matrix is the accumulated matrix from the beginning of the beam line and is never updated. This matrix will be printed any time A 13. 4. card is encountered and a beam update has occurred so that the RC Matrix has been redefined. This matrix is 6×6. In second order it has the same value of the 6×6 portion of the RC-Matrix if no updates had occurred.

SI-Matrix. The SI-Matrix is the beam ellipsoid matrix and is 6×6 in first order and 42×43 in second order. The square root of the diagonal elements represent the projections of the beam ellipsoid onto the coordinate axes of the six-dimensional particle phase space. The off-diagonal elements of the matrix represent the tilts of the ellipse in the various phase-planes. The centroid of the beam does not have to coincide with the center line of the magnets. The displacement of the centroid from the center line of the magnets may be defined by the 7. card and is altered by misalignments and second order transformations. This information is carried along as a vector appended to the beam matrix (SI-Matrix) and may be constainded.

T-Matrix. The T-Matrix is another name for the second order aberrations of the RC-Matrix. The elements T(I, J, K) give the J, K contribution to the I-th component of the vector space. The relative importance of the various second order aberrations may readily be evaluated by use of the 13. 42. data card which will scale the T Matrix by the initial sigma (beam) matrix, giving the T*SI matrix. Actually the component of T*SI are T*SI(IJK) = T (IJK)* SQRT(SI(JJ)SI (KK)) and give the relative importance of each aberration on the beam.

RTN-Matrix. This matrix is generated during a polygon calculation and represents the transformation between the 13. 5. and 13. 45. entry or on the teletype by POLYG or POLYG, MATRIX entry.

Numerical Nomenclature for Vector Space

The six-dimensional vector space, x, x', y, y', s, and δ will also have the numerical nomenclature, 1, 2, 3, 4, 5, and 6, so that if we wish to refer to the xx' phase space, we may say "12" or "21", or the x' δ space may be referred to as "26" or "62". The matrix element of the R-matrix that gives the dispersive contribution to the x' coordinate is $R_{x'\delta} \equiv R_{26}$. This numerical nomenclature for the vector space is most valuable in dealing with the second order aberration matrix T. For example,

$$X_i = \sum_j R_{ij} X_j + \sum_j \sum_k T_{ijk} X_j X_k .$$

Then if we wish to refer to the yy' contribution to x', the aberration coefficient is T_{234} and so forth for other coefficients.

OPTIMIZATION OF VARIABLES

To trace a particle represented by a vector V_0 through a drift space R_1, a quadrupole R_2, a drift space R_3, a bending magnet R_4, and a drift space R_5, each element of the system is represented by the appropriate transformation matrix R_i. Then the particle vector V at the end of the system will be given by

$$V = RV_0$$

where

$$R = R_5 R_4 R_3 R_2 R_1.$$

R is the total transformation matrix for the system. The matrix elements of each matrix are functions of the parameters of the system, i.e., the matrix elements of the drift space have as parameters the drift length while the matrix elements of a quadrupole lens have as parameters the field, aperture, and length of the lens. The energy of the particles determines the radius of curvature in the appropriate field regions.

In general the beam optician is not confronted with the problem of tracing a given particle or group of particles through a fixed system of magnets, but rather must determine the system parameters such as quadrupole fields and drift lengths so that a given particle vector at the beginning of the systems will arrive at a target or image space with specified values. This is the same as saying that the matrix R transforms the vector V_0 into the image space such that the new vector V has the desired properties. The matrix elements are complicated trigonometric and hyperbolic functions of the system parameters, so that after several matrix multiplications the matrix is too cumbersome to explicitly invert and solve for the desired parameters in terms of the given constraints. So numerical methods will be used in practice. What must be done is first to ensure that there is a sufficient number of variables to be adjusted to satisfy all constraints imposed on the system. Constraints are a specification of the location of foci, desired magnification of the beam, given value of a matrix element, etc. A variable is any system parameter that can be adjusted to give the desired result.

The procedure for the determination of values of variables required to satisfy a given number of constraints is best illustrated by example. Consider the problem of determining the currents i_1 and i_2 in a quadrupole doublet required to produce a horizontal and vertical focus. The focus condition is represented by

$$R_{12}\ (i_1,\ i_2) = 0$$
$$R_{34}\ (i_1,\ i_2) = 0.$$

We start by calculating ${}^{o}R_{12}$ and ${}^{o}R_{34}$ for some initial value of i_1 and i_2. These initial values may be pure guesses or approximations from ray traces.

$$ {}^{o}R_{12} = R_{12}\ (i_1,\ i_2) $$

$$ {}^{o}R_{34} = R_{34}\ (i_1,\ i_2). $$

Now perturb the values of i_1 and i_2 slightly and calculate new values of R_{12} and R_{34} for $i_1' = i_1 + di_1$ and $i_2' = i_2 + di_2$

$$ {}^{1}R_{12} = R_{12}\ (i_1',\ i_2) $$

$$ {}^{2}R_{12} = R_{12}\ (i_1,\ i_2') $$

$$ {}^{1}R_{34} = R_{34}\ (i_1',\ i_2) $$

$$ {}^{2}R_{34} = R_{34}\ (i_1,\ i_2')\ . $$

This determines the differential coefficients $\partial R_j/\partial i_2$ and $\partial R_j/\partial i_1$

$$ \frac{\partial R_j}{\partial i_1} = \frac{{}^{o}R_j(i_1, i_2) - {}^{1}R_j(i_1, i_2)}{i_1 - i_1'} $$

$$ \frac{\partial R_j}{\partial i_2} = \frac{{}^{o}R_j(i_1, i_2) - {}^{2}R_j(i_1, i_2')}{i_2 - i_2'} $$

where j stands for 12 or 34.

Then for some other change in i_1 and i_2, we have approximately

$$ \Delta R_{12} = \left(\frac{\partial R_{12}}{\partial i_1}\right)\Delta i_1 + \left(\frac{\partial R_{12}}{\partial i_2}\right)\Delta i_2 $$

$$ \Delta R_{34} = \left(\frac{\partial R_{34}}{\partial i_1}\right)\Delta i_1 + \left(\frac{\partial R_{34}}{\partial i_2}\right)\Delta i_2\ . $$

We now can find the values of Δi_1 and Δi_2 required to make $R_{12} = R_{34} = 0$ by setting $\Delta R_{12} = {}^{o}R_{12}$ and $\Delta R_{34} = {}^{o}R_{34}$

$$ R_{12} = \left(\frac{\partial R_{12}}{\partial i_1}\right)\Delta i_1 + \left(\frac{\partial R_{12}}{\partial i_2}\right)\Delta i_2 $$

$$ R_{34} = \left(\frac{\partial R_{34}}{\partial i_1}\right)\Delta i_1 + \left(\frac{\partial R_{34}}{\partial i_2}\right)\Delta i_2. $$

These are two equations in the two unknowns, Δi_1 and Δi_2. Here R_{12}, R_{34}, $R_{12}/\partial i_1$, $\partial R_{12}/\partial i_2$, etc., are considered numerical coefficients, so that we can solve for Δi_1 and Δi_2 by the methods of determinants. The values of i_1 and i_2 required to make R_{12} and R_{34} zero can be found, $i_1 = i_1 + \Delta i_1$ and $i_2 = i_2 + \Delta i_2$. In general the problem is nonlinear so that R_{12} and R_{34} are not zero as desired, but nonetheless, smaller than previously. The procedure is now iterated until the desired values of R_{12} and R_{34} are obtained. This determines the new values of the variables required to yield the given values of the constrained characteristics of the system.

When searching for the startup conditions that best fit the desired constraints, it is necessary to have a single number representing the "goodness of fit." TRANSPORT uses the root mean square deviation for this purpose. For clarity, consider a two-variable system x_1 and x_2 subject to two constraints m_1 and m_2. A Taylor series expansion around the starting point gives

$$dm_1 = \frac{\partial m_1}{\partial x_1} dx_1 + \frac{\partial m_1}{\partial x_2} dx_2$$

$$dm_2 = \frac{\partial m_2}{\partial x_1} dx_1 + \frac{\partial m_1}{\partial x_2} dx_2 .$$

Writing this in matrix form:

$$\begin{bmatrix} dm_1 \\ dm_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial m_1}{\partial x_1} & \frac{\partial m_1}{\partial x_2} \\ \frac{\partial m_2}{\partial x_1} & \frac{\partial m_2}{\partial x_2} \end{bmatrix} \begin{bmatrix} dx_1 \\ dx_2 \end{bmatrix} .$$

TRANSPORT evaluates the derivatives from analytic expressions for the transformation matrix elements and sets up the following (NxN) matrix:

$$A = \begin{bmatrix} dm_1 & \frac{\partial m_1}{\partial x_1} & \frac{\partial m_1}{\partial x_2} \\ dm_2 & \frac{\partial m_2}{\partial x_1} & \frac{\partial m_2}{\partial x_2} \end{bmatrix} .$$

Since the number of constraints and variables do not have to be equal, TRANSPORT uses a least squares procedure for finding the required change in the variables that best satisfy the constraints. If the tolerance S_j is assigned to each constraint, then the matrix whose inverse gives the required changes to the variable in order to satisfy the constraints is

$$C = A^T W A$$

where W is a diagonal standard deviation matrix

$$W = \begin{bmatrix} \frac{1}{S_1^{\,2}} & 0 \\ 0 & \frac{1}{S_2^{\,1}} \end{bmatrix} .$$

The S_j's have the significance that the jth constant should have the specified value $\pm S_j$. Performing the indicated multiplication gives a symmetric matrix whose lower triangular part is

$$C = \begin{bmatrix} \frac{\Delta m_2^2}{S_1^2} + \frac{\Delta m_2^2}{S_2^2} & & \\ \frac{\Delta m_1}{S_1^2}\frac{\partial m_1}{\partial x_1} + \frac{\Delta m_2}{S_2^2}\frac{\partial m_2}{\partial x_1} & \left|\frac{1}{S_1^2}\left(\frac{\partial m_1}{\partial x_1}\right)^2 + \frac{1}{S_2^2}\left(\frac{\partial m_2}{\partial x_1}\right)^2\right. & \\ \frac{\Delta m_1}{S_1^2}\frac{\partial m_1}{\partial x_2} + \frac{\Delta m_2}{S_2^2}\frac{\partial m_2}{\partial x_2} & \left|\frac{1}{S_1^2}\frac{\partial m_1}{\partial x_1}\frac{\partial m_1}{\partial x_2} + \frac{1}{S_2^2}\frac{\partial m_2}{\partial x_1}\frac{\partial m_2}{\partial x_2}\right. & \left|\frac{1}{S_1^2}\left(\frac{\partial m_1}{\partial x_2}\right)^2 + \frac{1}{S_2^2}\left(\frac{\partial m_2}{2x_2}\right)^2\right. \end{bmatrix}$$

The first row and first column are vectors that give the goodness of fit and negative one half the gradient of the vector space. The inverse matrix C^{-1} will give the required correction dX_j to the variables X_j to satisfy the constraints. The rms deviation to the constraints is

$$\delta = \sqrt{\frac{\sum_{j=1}^{k}\left(\frac{\Delta m_j}{S_j}\right)^2}{k}} = \sqrt{\frac{C(1,1)}{k}}$$

and the gradient is

$$g_j = -2C(j,1)$$

$$C^{-1} = \begin{bmatrix} k\,\delta^2 \\ dX_1 \\ dX_2 \\ \vdots \quad \ldots\ \text{residuals}\ \ldots \end{bmatrix}.$$

The differential matrices used by TRANSPORT in calculating the A matrix are given below for the various types of elements. The differential matrix for a bending magnet whose magnetic field is a variable can be written as

$$\frac{dm}{dB} = \begin{bmatrix} L\,R_{21} & LR_{11}-R_{12} & \frac{L}{\rho}R_{12}-R_{16} \\ R_{21}-\frac{L\omega^2}{\rho^2}R_{11} & LR_{21} & \frac{L}{\rho}R_{11} \\ 0 & 0 & 0 \end{bmatrix}\frac{\rho}{P}$$

If the field gradient n is varied instead, then

$$\frac{dm}{d\omega} = \begin{bmatrix} L R_{21} & L R_{11} - R_{12} & \frac{L}{\rho} R_{12} - 2 R_{16} \\ R_{21} - L R_{11} \frac{\omega^2}{\rho^2} & L R_{21} & \frac{L}{\rho} R_{11} - R_{26} \\ 0 & 0 & 0 \end{bmatrix} \frac{1}{\omega}$$

where $\omega = \sqrt{1-n}$ in the bend plane or $\omega = \sqrt{n}$ in the nonbend plane and the R_{jk}'s are the usual first order transformation matrix element for the magnet. Note that only the dispersive matrix elements differ for the differential matrices when B or n are considered variables. For a quadrupole, either the length or field may be varied. For a variable quadrupole length

$$\frac{dm}{dL} = \begin{bmatrix} R_{21} & R_{11} \\ -k^2 R_{11} & R_{21} \end{bmatrix}$$

where $k^2 = [\frac{1}{B\rho} \frac{dB}{da}]$. If the pole tip field is variable, the differential matrix is

$$\frac{dm}{dB} = \begin{bmatrix} L R_{21} & L R_{11} - R_{12} \\ R_{21} - k^2 L R_{11} & L R_{21} \end{bmatrix} \frac{1}{k} .$$

Variables and Vary Codes

Variables are parameters describing the beam line that the user will allow TRANSPORT to vary when attempting to satisfy constraints. A variable is designated by a non-zero vary code. Vary codes make up the decimal part of the unique type code assigned to each magnet type and may have the values 1 through 9. Each succeeding part of the decimal corresponds to the appropriate parameter in the parameter list for the type code, e.g., the first decimal place (.X) would designate the first parameter as a variable if $X \neq 0$, the second decimal place (.0X) would designate the second parameter as a variable if $X \neq 0$, etc. Consider a quadrupole (type code 5.) whose field is variable and is the second parameter on the parameter list, the type code would be written 5.0X with x = 1, 2, 3, ---9 to specify the field as a possible variable (e.g., 5.01). The length of the quadrupole is the first parameter in the parameter list and if both the length and field are variable the type code would be written 5.NM with N, M = 1, 2, ----9.

Often it is desirable to tie two or more variables together so that the same change is made to each variable. An example of this would be a symmetric triplet where the first and third quadrupoles must have the same field. This is accomplished by using the same digit (not 0 or 1) for the vary code of each quadrupole. A vary code of 0 specifies the corresponding parameter may not be varied. The vary code 1 specifies the corresponding parameter may be varied and does not couple to any other vary code of a type code. A vary code of 2 in the first

decimal part will couple to any other vary code of 2 in the first decimal part of any other type code but will not couple to a vary code of 2 in the second decimal part of a type code. Similarly for vary code of 3, 4, 5, 6, 7, 8 and 9. Vary codes 4 and 9 (also 3 and 8; and 2 and 7) will play a special role if used in the same decimal part of the type codes in that the correction added to the variable with vary code 4 will be subtracted from the variable with vary code 9, etc. This antisymmetric coupling can be prohibited by a 13. 50. entry. As an example, consider finding the location of the horizontal waist following a bending magnet. This may be accomplished by sliding the waist constraint (10.2.1.0. .01 card) along the beam line while maintaining the total beam line length:

```
3._____________
4.      L. B. N.
3.4     L1.              drift length L1 will be varied so
10.  2. 1. 0. .01        as to place the 10. data card at
3.9  L2.                 the horizontal waist such that
5._____________          L1 + L2 = constant.
3._____________
```

TRANSPORT allows a maximum of 10 variables.

Internal Constraint on Variables

Internal limits are placed on the values that variables may be assigned by TRANSPORT during optimization in order to prevent the mathematical procedures from assigning non-physical values to real parameters e.g., negative drift lengths, etc. Table 2 gives the beam element and the lower and upper limits on its variable parameter list. These internal limits may be altered by use of the 21. data element. The values specified on the data input need not be within the limits given in the table. The internal limits are only imposed during computer optimization. The limits are for whatever units are being used, so if magnetic field is in kilogauss, the variable quadrupoles will be limited to fields values between - 20 and + 20 kilogauss, whereas, if the magnetic field is in units of tens-of-kilogauss, the variable quadrupoles will be limited to field values between - 20 and + 20 tens-of-kilogauss i.e., - 200 to + 200 kilogauss.

When a user selects the variable metric optimization[6] package of TRANSPORT the allowed physical range $L_1 L_2$ of each variable j as defined by the internal constraint of the variable is transformed into a numerically infinite range. If D_j is the external variable and x_j is its internal value, then

$$x_j = \tan\left(\frac{D_j - L_{1_j}}{L_{2_j} - L_{1_j}}\,\pi - \pi/2\right)$$

such that

$$L_{1_j} \leq D_j \leq L_{2_j}$$

$$-\infty \leq x_j \leq +\infty .$$

This scaling of the variables requires a scaling of the gradient such that if f is the rms deviation, then the internally scaled gradient is

$$g_j = \frac{\partial f}{\partial D_j} \left(\frac{L_2 - L_1}{\pi} \right)_j \cos^2 \left[\pi \left(\frac{D - L_1}{L_2 - L_1} - \frac{1}{2} \right) \right]_j .$$

This mapping of the physically restricted range on to the infinite plane allows optimization in a multidimensional space without crashing into limits.

Table 2. Internal constraints on variables.

Element	JType	Variables	Lower	Upper	Lower	Upper
BEAM	1	1.111111	.01	1000.	Etc.	
POLE	2	2.1	-60.	60.		
DRIFT	3	3.1	.1	1000.		
BEND	4, 5, 6	4.011	-18.	18.	-500.	500.
QUAD	7, 8	5.11	.01	10.	-20.	20.
EXTRA	9, 10, 11					
ALIGN	12, 13	8.111111	-1.	1.	-50.	50.
			Repeat three more times			
AUX	14	14.111111	None	None		
SOL	15	19.11	None	None	None	None
ROT	16	20.1	-360.	360.		

Section 2 - Standard Data Input

TRANSPORT DATA DECK STRUCTURE

Each TRANSPORT data deck consists of a computer control card record and a TRANSPORT data deck record, with these two records separated by a end of record mark. The data record begins with a date and case number card (except the interactive TRANSPORTS, TRAN3 and TRAN4) and an unlimited number of data cases, each starting with a title card and ending with a sentinel card (or 73. card).

The input file structure is

Off-line	On-line
Date card	TITLE
1	0
TITLE	....
0	....
....	....
....	....
73.	73.
73.	EOF

The first data card of the off-line TRANSPORTS (TRAN2 and TRAN22) must be a comment card called the date card. The entry on this card will head each run made. Usually the comment is simply the date or the card may be left blank. The second card must be a case number card with any numeric entry which will be used as the starting value of the case number. This case number is automatically incremented for each new case read by TRANSPORT. Following these two special cards may come any number of stacked TRANSPORT data cases, each beginning with a title card/option card and ending with a terminator (sentinel or 73.) card. A double sentinel card terminates the job.

COORDINATE SYSTEM AND SIGN CONVENTIONS

Before describing the detailed data input to TRANSPORT a few words should be said about the coordinate system and the magnetic field sign conventions used by TRANSPORT.

Magnetic Field Sign. The following sign convention can be adopted for the magnetic fields:

Quadrupole field positive:	Horizontally converging
Quadrupole field negative:	Vertically converging
Bending magnet field positive:	Upward
Bending magnet field negative:	Downward

These conventions are true for both positive and negative particles by using a right handed coordinate system and right hand rule for positive particles with +x axis to left looking along +z and a left handed coordinate system and left hand rule for negative particles with +x axis to right looking along +z.

Coordinate System. The spacial coordinates are as follows:

+z axis: Direction of particle motion.

+y axis: Vertical displacement upward.

+x axis: Horizontal displacement, use left or right hand rule depending on sign of particles. Left hand rule for negative particles and right hand rule for positive particles.

Energy input. The particle energy can be used as input instead of the momentum by specifying the rest mass of the particle before a beam card via the 16. 18. data entry. The input of the rest energy must be in units compatible with the momentum units, and thus must follow any unit cards and preceed the beam card, e.g.,

```
Test energy input of 0.75 GeV protons
0
15. 1.
15. 11. GeV/c 1.
16. 18. 0.938213
1.  X. XP. Y. YP. S. δP/P. 0.750
.
.
.
73.
```

The use of negative momentum or energy is to change the sign of the particles sent through a given beam line. If a beam line is set up for a positive particle, negative particles can be sent through the beam line by setting P = -P. This has the effect of reversing the sign of all magnetic fields.

DATA INPUT FORMAT

All data input to TRANSPORT is read field free. As each card is read it is printed into the output stream. After completion of the reading, the entire data array is printed to give the data index count and names associated with each data line. During Option O input the data is placed sequentially into an array called the data array with location counter I. All data is placed into this array except vectors (22 element) and arbitrary matrices (25 element) which are stored in special arrays. A maximum of 300 numbers are allowed in the data array.

The field free input may begin in any column. All entries after a $ are ignored by TRANSPORT and may be used to place comments on the data cards. An unlimited number of comment cards, beginning with a $ may be placed anywhere in the data deck. Alpah-numeric blocks are separated by blanks and/or commas. Each data line (TRANSPORT element) is

entered on one card except possibly the 1, 12, and 25 elements, as explained elsewhere.

Numeric blocks consist of numbers or group of numbers which constitute the data input to TRANSPORT. These numbers may be integers (which will be considered as having unspecified decimal points and as such really be floating point numbers) floating point numbers, exponential numbers in any mixed order with the provision of repetition by use of the repeat specification (R).

Example:

Integers	- 1, 2, 25, etc. (interpreted as 1. 2. 25.)
Floating points	- 3.074 -5.2540 +.667 -0.0123
Exponentials	- +2.0123E-6, 1.2345E+4 1E6, +1E+4 etc.
Repeats	- 0R6, 6.7502R2 1.42E-3R4

OPTION 0, THE BASIC DATA DECK

The first card of each TRANSPORT data case of a title card and the second card is an option card.

Option 0 specified on the second card of a data deck is the standard data input option and specifies that the data following consists of a type code and parameter list as will be described shortly. The data read under the Option 0 input will form the nucleus of the Options 1, 2, 3, 4 and 5 data, should they be used.

The naming of a data line is optional. If one names the line, the name must begin with an alphabetic character and should not exceed six characters in length. If N is the usual number of entries of the particular data line, the name would be entered as the $N + 1^{\underline{st}}$ entry.

Two different types of input data cases can be used with TRANSPORT. The Option 0 cases define the user beam line, specifying the various magnets, input-output options, vectors and beam to be transformed, etc. The other options (1, 2, 3, 4, and 5) operate on the basic data deck as defined by Option 0. These other options allow the data deck to be modified in various ways and the calculations reperformed with the modified deck.

The basic beam line (Option 0) deck is built from the 27 different element types available to TRANSPORT. These 27 element types are presented in Table 3.

Table 3.

Element type	Meaning
1	Beam ellipsoid input
2	Bending magnet pole face rotation
3	Drift length
4	Bending magnet
5	Quadrupole magnet
6	Slit
7	Axis shift
8	Misalignment
9	Repetition
10	Constraint
11	Accelerator energy gain section
12	Beam correlation
13	Output specification
14	Arbitrary matrix
15	Unit change
16	Parameter input
17	Second order
18	Sextupole magnet
19	Solenoid magnet
20	Beam rotation
21	Stray field and miscellaneous input
22	Particle vectors
23	Particle separator
24	Plot options
25	Calculated matrix
26	Space charge
27	RF buncher

These elements will be described in more detail later.

The Option 1, 2, 3, 4, and 5 data decks allow the basic Option 0 data set to be manipulated or altered in the following manner:

Option 0	Input new beam and/or vectors
Option 2	---
ALINE	Add a line to the data
ALTER	Alter a parameter in the data
DLINE	Remove lines from the data
FIX	Fix variables and remove constraints
NAME	Rename the data
MOVE	Move several lines of data
PUNCH	Write data out to tape 7
POLYG	Calculate acceptance polygon
REVERSE	Reverse order of data in data array
Option 3	1, 2, 3, or 4 dimensional chi-square search
Option 4	Second order plotting and histrograms
Option 5	Calculate acceptance polygons

These operations will be described after the detailed description of the 27 basic TRANSPORT elements which follows.

Data is read by subroutine READX called from readin. The data is placed sequentially into an array called data with location counter I. All data is placed into the data array except vectors (22) and arbitrary matrices (25.) which are stored in special arrays. As the data is read it is printed, each type on a line. The readin of data continues until a sentinel or 73. data card is encountered.

The data array is then printed out in its entirety, giving the I counter as calculated by readin in the left most column, the data name as specified by the user or calculated by the code in the absence of a user name, followed by the type code and parameter list for each data card read. The reading of a type code 73. signifies the conclusion of the data input and transport then prints the total number a data numbers stored in the data array. This number must not exceed 300.

The I counter is the location of the type code of each data element and will be used by the Option 2 and Option 3 data input, i.e., if one wishes to refer to the magnetic field of the quadrupole (type code 5.) at I count 37 he will specify I count of 39, (37 + 2).

I	Name	Type code	Parameter list			
.		.	.			
.		.	.			
.		.	.			
35	(L1)	3.0	L.			
37	(Q1)	5.000	L.	B.	A.	
41.	(L2)	3.0	L.			I count 40
.		.				I count 39
.		.				I count 38
.		.				I count 37

1. NNNNNN X. X'. Y. Y'. dS. dP/P. P. — Beam Ellipsoid Input

Normally the first card in a data deck describes the beam ellipsoid to be transformed, specifying the projections on to the six coordinate axes and the central momentum of the beam. If the beam ellipsoid is not upright, the tilts (correlations) can be specified by the 12. data type. The units are those selected by any preceeding 15, data cards or the standard units of cm, mr, cm, mr, cm, percent and GeV/c by default.

N	= vary code, if N = 0 not variable.
X	= one half of horizontal beam projection.
$X' = dX/dZ$	= one half horizontal emergence.
Y	= one half of vertical beam projection.
$Y' = dY/dZ$	= one half of vertical emergence.
dS	= one half of longitudinal beam extent.
dP/P	= one half the normalized momentum spread.
P	= average momentum of beam.

The beam ellipsoid is represented in first order by TRANSPORT as a symmetric six dimensional matrix called the σ-matrix. It's construction is

$$\sigma = \begin{bmatrix} \sigma_{11} & & & & & \\ \sigma_{21} & \sigma_{22} & & & & \\ \sigma_{31} & \sigma_{32} & \sigma_{33} & & & \\ \sigma_{41} & \sigma_{42} & \sigma_{43} & \sigma_{44} & & \\ \sigma_{51} & \sigma_{52} & \sigma_{53} & \sigma_{54} & \sigma_{55} & \\ \sigma_{61} & \sigma_{62} & \sigma_{63} & \sigma_{64} & \sigma_{65} & \sigma_{66} \end{bmatrix}$$

Its off-diagonal elements are a measure of the tilt of the ellipsoid and the diagonal elements a measure of the projection of the ellipsoid onto the coordinate axes. For an initial upright ellipsoid we have

$$\sigma = \begin{bmatrix} X^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & X'^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & Y^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & Y'^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & dS^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & (dP/P)^2 \end{bmatrix}$$

In some beam lines it will be necessary to have more than one beam card as in a beam where the horizontal and vertical source are at different locations or where the beam ellipsoid is modified by the interaction with a target. In these cases the subsequent beam cards are followed by a ninth parameter specifying an rms addition to the beam ellipsoid. This ninth parameter is zero. As an example, consider a beam whose horizontal source is 39 inches before the vertical source 48 inches before a quadrupole. This system would be specified by the following

data cards:

```
1.   X.   X'.   0.   0.   0.   dP/P.   P.
3.   39.
1.   0.   0.    Y.   Y'.  0.   0.      0.   0.
3.   48.
5.   16.75      4.315     4.
.
.
.
.
.
```

As another example, consider a beam that passes through a target resulting in a multiple scattering increase in the phase space and an reduction in the beam momentum. The correlations are unaffected. Then the data card:

```
1.   dX.   dX'.   dY.   dY'.   dl.   δ(dP/P).   δP.   0.
```

With nine parameters rather than the usual eight placed at the target location produces an rms alteration of the beam. The beam would then be given by the matrix.

$$\sigma = \begin{bmatrix} (X)^2+(dX)^2 & & & & & \\ & (X')^2+(dX')^2 & & & & \\ & & (Y)^2+(dY)^2 & & & \text{(unaltered)} \\ & & & (Y')^2+(dY')^2 & & \\ & & & & (dS)^2+(dl)^2 & \\ & \text{(unaltered)} & & & & (dP/P)^2+(\delta(dP/P))^2 \end{bmatrix}$$

and transformed at a momentum $P + \delta P$. (δP would be negative).

The beam card may also be used to input betatron functions. In order to do this, the phase area in the two decoupled phase planes must be inserted before the beam card via a 21. 0. EX. EY. card, e.g.,

```
21.   0.   Ex.   Ey.
 1.   βx.  αx.   βy.   αy.   0.   0.   P.
```

Here α and β are the betatron functions and E_x, E_y are the phase areas divided by π and $\gamma = (1 + \alpha^2)/\beta$. The units will be the standard TRANSPORT units or as altered by any 15. data entries. In the absence of any unit change, the β's are in cm/mr, γ's in mr/cm, α's dimensionless, and E's in cm-mr.

The betatron functions along the beam line will be printed in a summary table, at the end of the TRANSPORT run. The Betatron functions are converted to the standard transport σ-matrix and are transparent to TRANSPORT, only being used for input-output convenience by the user.

2.N β. B2. Magnet Pole Face Rotation

Non-normal entry or exit into or from a bending magnet may produce first order focusing in either plane. The required parameters are the angle between the normal to the paraxial trajectory and the face plane of the magnet and the magnetic field inside and outside the magnet. The field inside the magnet will be taken from the magnet data card (4. card) and the field outside the magnet is specified as the third parameter B2 and is normally zero.

N = vary tag, β is variable if $N \neq 0$.

β = angle between normal to paraxial trajectory and magnet face in degrees. Angle with same sign as magnetic field will give positive vertical focusing.

B2. = field outside magnet, normally zero.

In a sequence of 2. and 4. data elements, a 2. element will be considered a entry rotation e.g., in the sequence 4., 2., 4., 2., 4. the grouping is (4.), (2., 4), (2., 4.)

The matrix representation for the 2. element is

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \frac{\tan\beta}{\rho} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{-\tan(\beta-\gamma)}{\rho} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where

$$\gamma = K_1 \left(\frac{2g}{\rho}\right) \frac{1+\sin^2\beta}{\cos\beta} \left[1 - K_1 K_2 \left(\frac{2g}{\rho}\right) \tan\beta\right]$$

and

$$\rho = P/e\,(B_m - B_2)$$

with

K_1 = fringing field parameter input by 16. 7. K_1. Default value = 0.5

K_2 = fringing field parameter input by 16. 8. K_2. Default value = 0.

B_m = Bending magnet field input by 4. L. B_m. N.

g = half vertical gap of bending magnet input by 16. 5. g.

P = particle momentum.

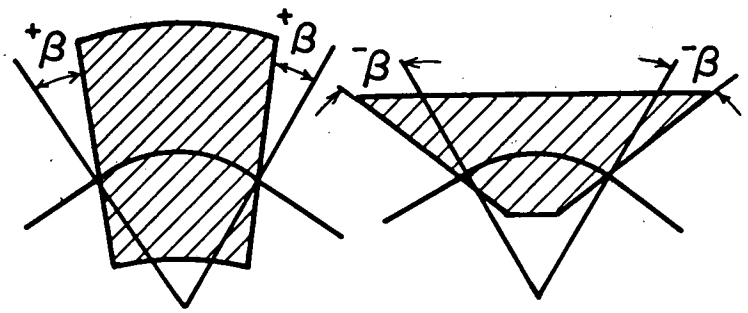
The pole face rotation may be varied by the program in attempting to satisfy the system constraints if the vary tag, N, is non-zero. Internal program constraints will constrain the absolute value of β to be less than 60 degrees if β is varied.

A pole face rotation (2. element) normally preceeds or follows a bending magnet (4. element). The only data cards which may be placed between a 2. and 4. data card describing a

magnet are up to fove 13. cards or five 2. cards. Any other card will cause a non-fatal error. The following sequences are allowed.

2.	β.	0.		-2.	β.	0.		
13.	8.			2.	β.	0.		
4.	L.	B.	N.	-2.	β.	0.		etc.
13.	8.			-2.	β.	0.		
2.	β.	0.		13.	8.			
				4.	L.	B.	N.	
				2.	β.	0.		

The sign convention for β is shown below



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with β giving vertical focusing when it has the same sign as the magnetic field.

3.N L. Drift Length

A field free region of length L is specified by the 3. data element. The units of L are specified as the eighth unit and is normally meters. The matrix is:

$$R = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The drift length may be varied if $N \neq 0$, i.e., 3.1 or 3.2 etc. designates a variable drift length of initial value L. The internal constraint built into TRANSPORT will place a lower limit on L of 0.1 units and an upper limit of 1000 units. If L is not a variable (N = 0) L may take any real value $-\infty < L < \infty$.

4.0KM L. B. N. Bending Magnet

A 4. data card specifies a bending magnet of normal entry and exit. If the paraxial trajectory does not make normal entry and exit a pole face rotation must be specified by a 2. data element. A negative length indicates a vertical bend. An upward field is taken as positive.

K = magnetic field vary code, if K = 0 B is not variable.

M = field index vary code, if M = 0 N is not variable.

L. = Effective length of field along trajectory in the same units as drift length, unit (8), normally meters.

B. = Average magnetic field along paraxial trajectory in units of unit (9), normally kilogauss.

N. = Magnetic field index $R(dB/dX)B^{-1}$ where R is the radius of curvature of the particles and dB/dX is the transverse gradient.

The first order matrix representation of a bending magnet is:

$$R = \begin{bmatrix} \cos K_x L & \frac{1}{K_x}\sin K_x L & 0 & 0 & 0 & \frac{1}{\rho K_x^2}(1-\cos K_x L) \\ -K_x \sin K_x L & \cos K_x L & 0 & 0 & 0 & \frac{1}{\rho K_x}\sin K_x L \\ 0 & 0 & \cos K_y L & \frac{1}{K_y}\sin K_y L & 0 & 0 \\ 0 & 0 & -K_y \sin K_y L & \cos k_y L & 0 & 0 \\ \frac{1}{-K_x\rho}\sin K_x L & \frac{1}{-K_x^2\rho}(1-\cos K_x L) & 0 & 0 & 1 & \frac{1}{\rho^2 K_x^3}(K_x L-\sin K_x L) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where ρ = radius of curvature = P/eB and

$$K_x^2 = (1-n)\,\rho^{-2}, \qquad K_y^2 = n\rho^{-2}.$$

The parameter list for the bending magnet may be changed by the 16. 21. data option so that any combination of length, bending angle or magnetic field may be used, see the 16. data input.

For realistic calculations a vertical gap correction must be made for the fringing field of bending magnets. For wedge magnets, this can be accomplished by use of the 16. 22. 1. data card which will produce a zero angle fringe field matrix at the entrance and exit of all subsequent bending magnets until explicitly tuned off by another 16. 22. data specification. Alternatively, a 2. 0. fringe matrix may be explicitly given at the entrance and exit to the wedge magnet.

A rectangular magnet that is symmetrically oriented so that the entrance and exit angles are each half the angle of bend may be specified by a 16. 22. 2. data card. Once the rectangular magnet specification is given, it will remain in effect until changed by a different 16. 22. data entry.

5. NM L. B. A. Quadrupole Magnet

A quadrupole produces first order focusing without deflection of the beam. A positive field, B, indicates a horizontally focusing lens while a negative field indicates a vertically focusing lens.

N = Length of quadrupole variable if $N \neq 0$.
M = Magnetic field of quadrupole variable if $M \neq 0$.

L. = Effective magnetic field length along Paraxial trajectory in the same units as drift lengths, unit (8).
B. = Magnetic field at pole tip of quadrupole in units of unit (9) normally kilgrauss.
A. = One-half the pole to pole gap, i.e., the radius of the inscribed circle in the same units as horizontal beam displacement, unit (1).

The first order matrix representation of a quadrupole magnet is

$$\begin{bmatrix} \cos K_x L & \frac{1}{K_x}\sin K_x L & 0 & 0 & 0 & 0 \\ -K_x \sin K_x L & \cos K_x L & 0 & 0 & 0 & 0 \\ 0 & 0 & \cos K_y L & \frac{1}{K_y}\sin K_y L & 0 & 0 \\ 0 & 0 & -K_y \sin K_y L & \cos K_y L & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where

$$K_x^2 = \frac{B}{Ar}$$

$$K_y^2 = -\frac{B}{Ar}$$

r = magnetic rigidity of beam ($r = B\rho = \frac{P}{e}$).

6. J. X. Y. Slit

This element is used to introduce appertures along the beam line for display and polygon calculation. It has no effect on the transformation matrix or beam matrix but will interact with the polygon calculation and vector tracking if the vectors exceed the specified aperture and the 16. 14. option is selected. The interpretation of X and Y is designated by the value of J and listed below:

J = 0	X = 1.	Updates beam. Reinitalizes RC transformation matrix. This is not a slit.
J = 0	X = 2.	Initiates the RC2 matrix. This is not a slit.
J = 0	X = 3.	Initialize R3 matrix.
J = 1	X	X = Horizontal half width of slit if y = 0.
J = 2	X.Y.	X and Y are the rectangular half apertures to be associated with the first element following which possesses length.

J = 3 X. X = vertical half width of slit if y = 0.

J = 4 X. Y. X and Y are the rectangular half widths of the slit of zero length.

J = 5. X. Y. X and Y are the half widths of an elliptical slit. Only used with vector 16. 14. option.

J = 6. X. Y. X and Y are the elliptical half apertures to be associated with the first element following which possesses length. Only used with vector 16. 14. option.

7. NNNNNN dX. dX'. dY. dY'. dS. dδP/P Axis Shift.

This element introduces a shift in the location of the beam centroid and introduces an update of the RC transformation matrix. The units are the same as for the beam matrix (1. data element).

N = vary code, if N = 0 parameter not variable

dX = horizontal phase space displacement of beam centroid

dX' = horizontal divergence displacement of beam centroid

dY = vertical phase space displacement of beam centroid

dY' = vertical phase space divergence displacement of beam centroid

dS = longitudinal phase space displacement of beam centroid

δdP/P = momentum displacement of beam centroid

The axes shifts (X_j) are added to the beam centroid vector (seventh column of σ matrix) and added quadratically to the beam ellipsoid. The transformation for i = 1, 6: J = 1, 6 is

$$\sigma_{ij} = \sigma_{ij} + X_j X_i + \sigma_{i7} X_j + \sigma_{j7} X_i .$$

$$\sigma_{i7} = \sigma_{i7} + X_i$$

On output, the centroid transformations are

$$r_{ij} = (\sigma_{ij} - \sigma_{i7}\ \sigma_{j7})/\sqrt{(\sigma_{ii} - \sigma_{i7}^2)(\sigma_{jj} + \sigma_{j7}^2)} \quad i \neq j$$

$$\sigma_{jj} = \sqrt{\sigma_{jj} + \sigma_{j7}^2} .$$

The element has no effect on the value of the several transformation matrices or on vector calculations.

8. VVVVVV X. θ. Y. φ. S. ψ. NMP. Misalignment

The 8 element allows the user to investigate the effect upon the beam of a misalignment of an individual magnet or group of magnets by either uncertainties in their locations or by a deliberate displacement. The misalignment element does not effect the transformation matrix and so has no effect on the transformation of particle vectors except it does produce an update of the RC matrix. The input parameters are given below and assume the horizontal and vertical phase planes are in the same units.

V = vary code, if V = 0, parameter not variable.

X. = horizontal displacement in units of horizontal beam extent, normally cm, unit (1).

θ. = rotation about horizontal axis in units of horizontal beam divergence, normally mr, units (2).

Y. = vertical displacement in units of horizontal beam extent, normally cm, unit (1).

ϕ. = rotation about vertical axis in units of horizontal beam divergence, normally mr, unit (2).

S. = longitudinal displacement in units of horizontal beam extent, normally cm, unit (1).

ψ. = rotation about longitudinal axis in units of horizontal beam divergence, unit (2).

NMP. = Type of misalignment:

N = 0 uncertainty in position.

N = 1 deliberate displacement.

M = 0 use original axis for succeeding magnets.

M = 1 use new misaligned axis for succeeding magnets.

P = 0 misalignment based on R matrix.

P = 1 misalignment based on RC matrix

P = 2 misalignment based on RC2 matrix.

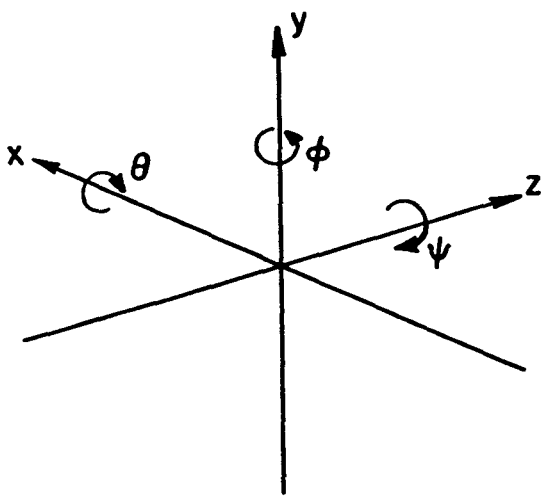

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Fig. 6. Definition of axis and rotations for magnet misalignments showing directions of positive value.

The various misalignments may be altered by TRANSPORT by flagging them as variables by making the appropriate V non-zero, e.g., if the value of the horizontal displacement is to be varied to produce a centroid shift of 0.1 inches the following data pertains:

find misalignment for centroid shift of 0.1	find misalignment for centroid uncertainty of 0.1
0	0
1. XX' YY' S dp P	1. 0. 0. 0. 0. 0. 0. P
|	|
6. 0. 1.	6. 0. 1.
5. L B A	5. L B A
8.1 0.9 0.0. 0.0. 0. 100.	8.1 0.9 0. 0. 0. 0. 0. 1.
|	|
10. 7. 1. 0.1 .01	10. 7. 1. 0.1 .01

9. N. Repetition

If a group of data elements is to be repeated, an economy in input is provided by the repetition element 9. This card specifies that all the data following it up to a 9. 0. data card shall be repeated N times. These repetition groups may be nested four deep. Consider the following example showing two identical data structures of the same beam:

```
 3.
 5.
 3.
 2.
 4.
13.
 3.
 2.
 4.
13.
 3.
 5.
 3.
 5.
 3.
 5.
 3.
 2.
 4.
13.
 3.
 2.
 4.
13.
 3.
 5.
 3.
 5.
```

```
 9.      2.
 3.
 5.

 9.      2.
 3.
 2.
 4.
13.
 9.      0.
 9.      2.
 3.
 5.
 9.      0.
 9.      0.
```

10.N J. K. X. δX. Contraint

TRANSPORT allows many quantities to be constrained. These divide into three general types, constraint of non-matrix system parameters, constraints on system matrices and constraints on linear combinations of system matrices. J., K. specify which quantity is to be constrained to the value $X \pm \delta X$. The decimal part of the type code, N, specifies if the constraint is an actual constraint N = 0; upper limit N = 2; or a lower limit N = 1.

Of the first type of constraint, only the length of the system with variable drift lengths may be constrained.

Of the second type of constraint, TRANSPORT allows constraints on the beam matrix (σ-matrix), the accumulated transformation matrix 1 (RC-matrix), the accumulated transformation matrix 2 (RC2-matrix), and the betatron functions β, α, γ, η and η'.

Linear combination of matrix elements are often constrained and comprise the third type of constraint. For any matrix between two waists, the phase advance is:

$$\psi = \frac{1}{2} \cos^{-1}[R_{11} R_{22} + R_{12} R_{21}].$$

If the two waists are identical

$$\psi = \cos^{-1} \frac{1}{2} (R_{11} + R_{22}).$$

Or the linear combination of transformation matrix elements

$$K M(A, B) + M(C, D) = x \pm \delta x$$

can be constrained, where M is the RC, RC2, or SI matrix for the data input of 16. 25. 1., 16. 25. 2., or 16. 25. 3. respectively, and J = ABCD. When the general phase advance is to be constrained the 16. 25. 4. data entry is used. Then

$$K \mu + \mu_2 = x \pm \delta x$$

where

$$\mu = \frac{1}{4\pi} \cos^{-1} \{RC(A, A)\, RC(B, B) + RC(A, B)\, RC(B, A)\}$$

$$\mu_2 = \frac{1}{4\pi} \cos^{-1} \{RC_2(C, C)\, RC_2(D, D) + RC_2(C, D)\, RC_2(D, C)\}.$$

Type of constraint	Constrained parameter	Value of J and K	Comments
System length	L	0 0	
Auxiliary accumulated Transfer matrix	RC2(J, K)	-(J+20), K	J, K=1, 2, 3, ---6
Betatron phase angle	ϕ_{JK}	-(J+10), K	$\cos(2\pi\phi_{JK}) = 1/2$ [RC(J, J)+RC(K, K)]
Transformation matrix	RC(J, K)	-J, K	
Beam matrix Projections Covariance	σ(J, K)	J, K J=K J>K	J may equal 7 for centroid of beam
Correlation of beam	r_{jk}	(J+10), K	$r_{jk} = \frac{\sigma_{jk}}{\sqrt{\sigma_{jj}\,\sigma_{kk}}}$
Betatron functions	$\beta_x, \alpha_x, \gamma_x$ $\beta_y, \alpha_y, \gamma_y$ $\eta_x, \eta_{xp}, \eta_y, \eta_{yp}$	(J+20), K	(J+20, K)=(21, 1),(22, 1), (22, 2) (J+20, K)=(23, 3),(24,3), (24,4) (J+20, K)=(21,6), (22,6), (23, 6), (24, 6)
Combination of matrix elements, K is floating point.	K RC(A, B)+RC(C,D)	ABCD, K	

11. L. DP. Phase. WAVEL. Accelerator Energy Gain Section

The effect of an accelerator section is simulated by the 11. element. This element alters the beam momentum, size and divergence. The matrix for the accelerator for a fully relativistic beam is

$$\begin{bmatrix} 1 & \frac{LP}{dP\cos\phi}\ln\left(1+\frac{dP\cos\phi}{P}\right) & 0 & 0 & 0 & 0 \\ 0 & \frac{P}{P+dP\cos\phi} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & \frac{LP}{dP(\cos\phi)}\ln\left[\frac{dP\cos\phi}{P}+1\right] & 0 & 0 \\ 0 & 0 & 0 & \frac{P}{P+dP\cos\phi} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \frac{dP\sin\phi 2\pi}{(P+dP\cos\phi)\lambda} & \frac{P}{P+dP\cos\phi} \end{bmatrix}$$

L = length of accelerator cavity in units specified by unit (8), normally meters.

dP = momentum gain in units specified by unit (11), normally GeV/c.

Phase = phase of cavity in degrees.

Wavel = RF wave length in units of longitudinal spread specified by unit (5), normally CM.

If the particle rest mass has been defined by the 16. 18. RESTM. Card dP and P of the beam will be interpreted as the energy rather than momentum.

12. (r_{ij}, i = 2, 6, J = 1, i - 1) Beam Correlation

The beam ellipsoid may be tilted in any of the 15 phase planes corresponding to the six-dimensional ellipsoid. These correlations are specified by the 12. data element giving the 15 r_{ij} where

$$r_{ij} \equiv \frac{\sigma_{ij}}{\sqrt{\sigma_{ii}\ \sigma_{jj}}} .$$

These correlations are dimensionless and are given in the following order;

12. r_{21} r_{31} r_{32} r_{41} r_{42} r_{43} r_{51}

r_{52} r_{53} r_{54} r_{61} r_{62} r_{63} r_{64} r_{65}.

The 12. data card must immediately follow the beam card whose parameters σ_{kk} will be used to calculate the σ_{ij} from the given r_{ij}.

The input for the 12. element may appear on one or two data cards. If two data cards are used, the first card must have exactly eight entries. For example, all three of the following would give identical results:

12. r_{21} 0 0 0 0 r_{43} 0
0 0 0 r_{61}

or 12. r_{21} OR4 r_{43} OR r_{61} OR4 NAME

or 12. r_{21} OR4 r_{43} OR4 r_{61} .

13. J. Output Specification

The 13. element allows the user to suppress various output normally generated by TRANSPORT or to initiate output not normally generated. The action introduced as listed below for the various values of J.

J. MEANING

1. Temporary override of suppression of beam ellipsoid output.
2. Suppress beam ellipsoid output. 2.1 will also suppress beamline graph.
-2. Suppress all output on first run through before optimization. Normal output after optimization with beam ellipsoid output suppressed except where specified by 13. 1. or 13. 3. option.
3. Permanent override of beam ellipsoid output suppression.
4. Print accumulated transfere matrix, RC, from last beam update and total accumulated transfere matrix from beginning of beam line if the RC matrix has been updated.
5. Aperture transformation orgin. Specifies location on beamline where all apertures subsequently encountered will be transformed back to in the horizontal and vertical phase space.
6. Print phase space aperture polygons at the locations of the 13. 5. and/or 13. 6. data cards during Option 5 calculations.
7. Momentum (energy) spectrum. Print phase space aperture polygons at the locations of the 13. 5. and/or 13. 7. data locations at each of the momentum specified by the 24. 4. data card during performance of Option 5 calculations.
8. Print the transformation matrix, R, of the preceding element.
9. Sets R1P true
10. Quadrupole aperture constraint flag. Generates a beam projection constraint (10. 1. 1. or 10. 3. 3.) at entrance and/or exit of any quadrupole if the X or Y beam projections exceeds the quadrupole aperture. This option replaces the conditional constraint at quadrupole entrance and exit as shown below:

13.	10.							
				10.2	1.	1.	A1	A1/10
				10.2	3.	3.	A1	A1/10
5.	L	B	A1	5.	L	B	A1	
				10.2	1.	1.	A1	A1/10
				10.2	3.	3.	A1	A1/10
				10.2	1.	1.	A2	A2/10
				10.2	3.	3.	A2	A2/10
5.	L	B	A2	5.	L	B	A2	
				10.2	1.	1.	A2	A2/10
				10.2	3.	3.	A2	A2/10

11. CalComp envelope trace - not available
12. CalComp layout - not available
20. Initalize misalignment pivot matrix R
21. Initalize misalignment pivot matrix RC

22. Initalize misalignment pivot matrix RC2
24. Print transform matrix 2, RC2 matrix. This matrix originates as a unit matrix at the location of a 6. 0. 2. data card and may be constrained.
25. Suppress vector output. This does not terminate vector transformations so output may be requested further along the beam line by the 13. 27. or 13. 26. data cards.
26. Permanent override of vector output suppression.
27. Temporary override vector output suppression so as to print vector output at this location.
28. Suppress print out of transformed aperture polygon plots but do not suppress polygon vertices or solid angle print out.
29. Suppress aperture calculation at location of 13. 5. data cards plot the polygons.
30. Produce aperture calculation at location of 13. 6. or 13. 7. data card, plot the polygons.
31. Adjust horizontal vista phase plot scale so vectors and beam ellipse are within boundary.
32. Adjust vertical vista phase plots scale so vectors and beam ellipse are within boundary.
33. Plot phase space ellipse without centroid shifts at locations specified by 24. ijkl.
34. Plot beam line without centroid shifts if a 24. 0. card is used.
40. Print the RC and R matrix after every element possessing a matrix. Turn off RC, R matrix output with A 13. -40. data entry.
42. Print the RC matrix scaled by the second order sigma (beam) matrix.
45. Print the polygon transformation matrix originating at the 13. 5. data location.
46. Suppress projection of x, y onto global coordinate system.
48. Print first order R matrix suppressing second order print out.
49. Print out optimization matrix, i.e., $\partial C_j / \partial V_k$.
50. Uncouple anti-connected variables, i.e., vary codes (9, 4), (8, 3) and (7, 2) are no longer coupled.

NIJK. used by second order vista transport (TRAN32) to store element T(IJK) in vector position N. The value of N is given in table below.

N \ Vector number M	1	2	3	4	5	6
Horizontal plane	1	3	5	7	9	11
Vertical plane	2	4	6	8	10	12

14. NNNNNN R(J, 1). R(J, 2). R(J, 3). R(J, 4). R(J, 5). R(J, 6). J. Arbitrary Matrix

An arbitrary transformation matrix may be specified by either the 14. or the 25. data element. The 14. data element defines a unit matrix with one or more non-unit matrix rows J given by the one or more successive 14. data cards. The units of the matrix elements are those appropriate for the units selected for the beam card (data element 1.). The matrix elements may be varied by making the appropriate N non-zero, e.g., if R(2, 2) is to be varied the data card would be 14.01 R_{21}. R_{22}. R_{23}. R_{24}. R_{25}. R_{26}. 2. As an example, consider a typical bending magnet matrix with rows 1, 2, 3, and 4 of non-unit matrix structure:

14.	$R_{11.}$	$R_{12.}$	0.	0.	0.	$R_{16.}$	1.
14.	$R_{21.}$	$R_{22.}$	0.	0.	0.	$R_{26.}$	2.
14.	0.	0.	$R_{33.}$	$R_{34.}$	0.	0.	3.
14.	0.	0.	$R_{43.}$	$R_{44.}$	0.	0.	4.

The rows number is given by the eighth parameter J. Rows 5 and 6 will be zero except for R(5, 5) = R(6, 6) = 1. If two arbitrary matrices are to follow each other they must be separated by some non-14. data card, such as a 13. or 16. card.

The units of the arbitrary matrix may be confusing if one is working in a non-natural set of units. This confusion can be reduced by recalling the matrix expansion of a particle vector:

$$X = R_{11} X_0 + R_{12} X_0' + R_{16}\, dP/P$$

$$X' = R_{21} X_0 + R_{22} X_0' + R_{26}\, dP/P.$$

If the arbitrary matrix has been calculated in natural units, say cm, radians and fractions for x, x' and dP/P and is to used in transport with the standard units of cm, mili-radians, and percent, then

$$R = \begin{bmatrix} R_{11} & .001\, R_{12} & .01\, R_{16} \\ 1000\, R_{21} & R_{22} & 10\, R_{26} \\ 0 & 0 & 1 \end{bmatrix}.$$

15. J. DIM. X. Unit Changes

TRANSPORT can work in any set of units. The units that will be used in the absence of an explicit unit change are called standard units; these are as shown below.

Quantity	Sumbol	Code number	Standard unit
Horizontal extent	X	1	cm
Horizontal divergence	X'	2	mr
Vertical extent	Y	3	cm
Vertical divergence	Y'	4	mr
Longitudinal spread	dS	5	cm
Momentum spread	dP/P	6	percent
Not used	---	7	---
Drift length	L	8	meters
Magnetic field	B	9	kilogauss
Mass	M	10	electron mass
Momentum of beam	P	11	GeV/c

When N units are to be changed the unit cards must be preceded by a 15. N. X. data card specifying that N 15. data cards follow. If X is nonzero the units will be restored to the standard values before processing the N units change cards. This allows a restoring of any unit changes made in previous data decks. Once a unit change has been made, it will remain until explicity changed again, so it is not necessary to change units in each data deck processed by TRANSPORT. The meaning of the parameters on the 15. data card are:

J = code number.

DIM = arbitrary Hollerith code for units used e.g., cm, In, GeV/c etc. should be less than 7-characters.

X = factor which multiplies new unit to give the standard unit, e.g., if the new unit is inches, then X = 2.54 cm/inch.

Consider the example of a data decks whose drift length is in feet, inches, and meters. The decks would be:

```
15.  1.   1.
15.  8.   FT    .3048    Since   0.3048  M/ft
|
15.  1.
15.  8.   IN    .0254    Since   0.0254  M/inch
|
15.  1.
15.  8.   M     1.       Since   1.0     M/M.
|
73.
```

Unit change from standard units to IN, MR, %, MeV/c.

```
15.  5.
15.  1.   IN     2.54
15.  2.   MR     1.
15.  6.   PC     1.
15. 11.   MeV/c  .001
15.  8.   IN     .0254
```

to change back to standard units use 15. 0. 1. 1., or, explicitly

```
15.  5.   BLK    1.
15.  1.   CM     1.
15.  2.   MR     1.
15.  6.   PC     1.
15.  8.   M      1.
15. 11.   GeV/c  1.
```

Table 4. Conversion value X for unit change card, i.e., 15. J. DIM. X. where X multiplies new unit to convert to standard unit.

Index	Standard unit \ New Units	Inches	Feet	Hundreds of inches	Radians	Fraction	Gauss	MeV	KeV
1	cm	2.54	30.48	245.					
2	mr				1000.				
3	cm	2.54	30.48	254.					
4	mr				1000.				
5	cm	2.54	30.48	254.					
6	%					100.			
7	---								
8	M	.0254	.3048	2.54					
9	Kg						.001		
10	electron mass								
11	GeV							.001	10^{-6}

16. J. X. Parameter Input

Various parameters used in evaluating the beam line can be specified via the 16. element. The parameter is designated by the value of J and the value of the parameter given by X.

J	Quantity	Interpretation
1	β.	Quadratic term in the bending magnet field (Sextupole Component) where the expansion of the bending field on the median plane is $$B_z = B_o[1 - n(\frac{x}{\rho}) + \beta(\frac{x}{\rho})^2 + \cdots]$$ $$n = -\frac{\partial B}{\partial R}\frac{R}{B}, \text{ and } \beta = \frac{\partial^2 B}{\partial R^2}\frac{R^2}{B}$$
2.	DB.	Error in bending magnet field. Sets $\sigma(6,6) = DB^2$, updates beam.
3.	SM.	Mass of particles in units of the electron mass. This parameter is used when evaluating the longitudinal spread of the beam.
4.	AP(1).	Horizontal half aperture. Once introduced it will be used for all subsequent bending magnets until altered by another 16. 4. data card. Effects only acceptance polygons, vector loss calculations and beam line plots.

5. AP(2) Vertical half aperture. Once introduced it will be used for all subsequent bending magnets until altered by another 16. . data card. This option produces an important correction to the matrix calculation for a 2. element which includes the effect of a finite fringe field.

6. LC. Input of accumulated length of system. Normally used to give length up to the starting point of current beam line.

7. FR1. Fringing field correction for trajectory bending in magnet fringe field, normally FR1 = 0.5.

$$FRI = \int_{-\infty}^{+\infty} \frac{B_y(z)(B_o - B_y(z))}{g\, B_o^2}\, dz$$

g is the vertical half gap given by a 16. 5. g. card.

8. FR2. Fringing field correction for trajectory bending in magnet fringe field, normally zero.

9. RDL. Introduces a random gaussian uncertainty in drift length of standard deviation RDL.

10. RDB. Introduces a random gaussian uncertainty in quadrupole fields of standard deviation RDB.

11. RDT. Introduces a random gaussian uncertainty in beam rotation of standard deviation RDT.

12. RAB1. Curvature of the entrance face of a bending magnet (reciprocal of radius of curvature) taken as positive for convex curvatures.

13. RAB2. Curvature of the exit face of a bending magnet. Taken as positive for convex curvatures. Producing a sextupole strength $k_s^2 L = -.5h(RAB)\, SEC^3\beta$.

14. Causes seventh component of vector to be set to system length if vector exceeds an aperture. The length will be positive if the exceeded aperture is horizontal and negative if vertical.

15. FOCLTL. Rotates the focal plane so second-order aberrations may be printed on the focal plane.

16. APFILL. Specifies the factor by which the quadrupole aperture (gap on 5. data card) is to be multiplied in calculating of acceptance polygons and beam line plotting. This option has no effects on matrices or vectors and does not affect the gradient of the quadrupole.

17. LENGTH. Length of following element. Use to give length to a magnetic element whose matrix is given by a 14. or 25. element.

18. EREST. When EREST=Rest energy of particle the eighth parameter on the beam card will be the particle kinetic energy rather than momentum. Also the momentum spectrum is converted to an energy spectrum. (24. 4.)

19. MBE When doing betatron functions, plot betatron function if MBE = 1.

20. BSEPR. Separator action flag.
BSEPR = -1 normal transformation of beam and vectors
= 0 shift vectors
= 1 shift beam.

21. ACP3. Specifies the parameter interpretation for a bending magnet. Normally a bending magnet is specified by the length L, bend field B, and field index N. Often a user knows the length L and angle of bend A. In order to ease input the 16. 21. option allows any combination of L, B, or A.

ACP3 = 0	Bending magnet parameters	4. L. B. N.
ACP3 = 1	Bending magnet parameters	4. A. B. N.
ACP3 = 2	Bending magnet parameters	4. L. A. N.

The field may not be varied when ACP3 $\neq$ 0.

22. ACP2. ACP = 0 Standard TRANSPORT wedge bending magnet with no vertical fringe correction.

22. ACP2. ACP2 = 1 Wedge bending magnet with automatic vertical fringe field correction the same as would be produced by a preceding and following 2. 0. 0. entry.

ACP2 = 2 Rectangular bending magnets with automatic calculation of fringe field matrix (type 2) of half bend angle at entrance and exit to each magnet. Magnets may not be split without fringes being introduced.

23. VEC. VEC = 0 Vectors transformed without space change.

VEC = 1 Vectors transformed with space change.

25. KONGARN Used to specify which matrices will be used in linear constraints. See the 10. data element.

KONGARN	1	RC Matrix
KONGARN	2	RC2 Matrix
KONGARN	3	SI Matrix
KONGARN	4	Phase advance

26. FE31. Varmit optimization is terminated if chi-square does not improve by FE31*100 percent in three tries.

27. RMSDEV. Terminate varmit optimization when the RMS deviation to constraints is less than RMSDEV. Normally RMSDEV = 1.

28. K STEPRM. Random step size that varmit will make if it fails to find a satisfactory RMS deviation. STEPRM determines the maximum step size, not the direction. Normally STEPRM = 1. If K $\neq$ 0, then this STEPRM is for the K-th variable only.

29. OPTYPE.

OPTYPE = 0	Use standard transport optimization routines.
OPTYPE = -1	Use varmit optimization routine.
OPTYPE = 1	Use varmit optimization and then the transport optimization. Normally OPTYPE = 0.

30. IWRITE. Output control.

31. CLOCK. CLOCK = maximum number of iterations that varmit will be allowed to find an RMS Deviation RMSDEV., normally CLOCK = 200.

32. ICNVRG. Terminate varmit optimization if the RMS does not improve by more than FE31 in ICNVRG + 3 trys. Normally ICNVRG = 0.

33. IRNDM. Maximum number of randon steps that should be taken if a satisfactory RMS Deviation is not found. Normally IRNDM = 0.

KLM. IJ. Storage into A-table of any element of the RC, RC2, R3, SI, correlation matrix, or VECTOR.

K = Ray number for storage
L = Plane for storage =1(x) =3(y)
M = Storage type

M = 1	RC(I, J)
M = 2	RC2(I, J)
M = 3	R3(I, J)
M = 4	SI(I, J)
M = 5	Correlation r_{IJ}
M = 6	VECTOR I, Position J.

17. λ_1. λ_2. λ_3. Second Order

The second order calculation is initiated by the 17. data card. This data card must not preceed the beam card if second order effects are to be included in the sigma matrix. A 13. 42. data card will print the second order transfer matrix scaled by the beam matrix in addition to the normal RC matrix. Second order vectors can be used to track system aberrations.

The 17. element introduces the second order calculation[3] by producing an increase in the dimensionality of the vector space from 6 to 42. The code speed is reduced by about 40 due to the larger vector space and consequently higher dimensional matrices used. λ1, λ2, and λ3 are the second, third and fourth moments of the momentum distributions all other distributions are assumed Gaussian. For a Gaussian momentum distribution $\lambda_1 = 1$, $\lambda_2 = 0$, and $\lambda_3 = 3$.

18. L. B. A Sextupole Magnet

The sextupole magnet differs from a drift length only in second order. The sextupole may not be varied.

L = effective length of sextupole field in same units as drift length.
B = magnetic field at pole tip in units of unit (8), normally kilogauss.
A = half aperture in same units as horizontal beam dimension.
the half aperture is the radius of the inscribed circle.

To first order, the matrix for a sextupole is

$$R = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The sextupole introduces terms into the second order T - matrix. These terms may be evaluated from the focusing strength defined as

$$k^2 = \left(\frac{B}{A^2}\right) \frac{1}{R}$$

where ρ is the radius of curvature of the particle in field B and R the magnetic rigidity $B\rho$.

$T_{111} = -\frac{1}{2}k^2L^2$ $T_{211} = -k^2L$ $T_{313} = k^2L^2$ $T_{413} = 2k^2L$

$T_{112} = -\frac{1}{3}k^2L^3$ $T_{212} = -k^2L^2$ $T_{314} = \frac{1}{3}k^2L^2$ $T_{414} = k^2L^2$

$T_{122} = -\frac{1}{12}k^2L^4$ $T_{222} = -\frac{1}{3}k^2L^3$ $T_{323} = \frac{1}{3}k^2L^3$ $T_{423} = k^2L^2$

$T_{133} = -\frac{1}{2}k^2L^2$ $T_{233} = k^2L$ $T_{324} = \frac{1}{6}k^2L^4$ $T_{424} = \frac{2}{3}k^2L$

$T_{134} = -\frac{1}{3}k^2L^3$ $T_{234} = k^2L^2$

$T_{144} = \frac{1}{12}k^2L^4$ $T_{244} = \frac{1}{3}k^2L^3$

19. NM L. B. Solenoid Magnet

The solenoid provides simultaneous focusing in both the horizontal and vertical phase planes. It also produces a mixing of the two planes. Both the length and/or field of the solenoid may be varied by setting N and/or M non-zero, such as 19.01, etc.

L = effective length of solenoid in same units as drift length.

B = magnetic field on axis of solenoid in units of unit (9), normally kilogauss.

$$R = \begin{bmatrix} \cos^2 KL & \frac{1}{K}\sin KL\cos KL & \sin KL\cos KL & \frac{1}{K}\sin^2 KL & 0 & 0 \\ -K\sin KL\cos KL & \cos^2 KL & -K\sin^2 KL & \sin KL\cos KL & 0 & 0 \\ -\sin KL\cos KL & -\frac{1}{K}\sin^2 KL & \cos^2 KL & \frac{1}{K}\sin KL\cos KL & 0 & 0 \\ K\sin^2 KL & -\sin KL\cos KL & -K\sin KL\cos KL & \cos^2 KL & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where $K = B/2R$, R = magnetic rigidity of the beam = $B\rho$. The solenoid may be thought of as a focusing element in each phase plane which produces a coupling between planes. This is explicitly demonstrated by writing the solenoid matrix as the product of a focusing matrix followed by a rotation of + KL

$$\begin{bmatrix} \cos KL & 0 & \sin KL & 0 & 0 & 0 \\ 0 & \cos KL & 0 & \sin KL & 0 & 0 \\ -\sin KL & 0 & \cos KL & 0 & 0 & 0 \\ 0 & -\sin KL & 0 & \cos KL & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos KL & \frac{1}{K}\sin KL & 0 & 0 & 0 & 0 \\ -K\sin KL & \cos KL & 0 & 0 & 0 & 0 \\ 0 & 0 & \cos KL & \frac{1}{K}\sin KL & 0 & 0 \\ 0 & 0 & -K\sin KL & \cos KL & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

20. N θ. Beam Rotation

The 20. element introduces a rotation in the X-Y plane. This rotation causes a mixing of the horizontal and vertical plane. θ is the angle of rotation in degrees taken as positive in clockwise direction as one looks along the positive Z axis. If $N \neq 0$, θ is a variable. The matrix representation for the 20. element is:

$$R = \begin{bmatrix} \cos\theta & 0 & +\sin\theta & 0 & 0 & 0 \\ 0 & \cos\theta & 0 & +\sin\theta & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 & 0 & 0 \\ 0 & -\sin\theta & 0 & \cos\theta & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

A rotation of 90 degrees interchanges the X and Y coordinates and may thus be used to introduce a vertical bend. The following two data sets produce identical results:

20.	90.		-------
2.	1.	2.	1
4.	L. B. N.	4.	-L. B. N.
2.	2.	2.	2.
20.	-90.		-------

Normally the plots produced by the 24.0. option will have the X, Y coordinates projected onto the global coordinate system. This projecting can be turned off by use of a 13. 46. data option.

21. J. EPS. DEL. — Stray Field and Miscellaneous Input

The 21. data card is used to input various miscellaneous parameters to TRANSPORT depending on the value of J.

J = 4	Horizontal stray magnetic field
J = 2	Vertical stray magnetic field
J = 0	Input Betatron function phase area
J < 0	Alter interval limits on variables

When J > 0, the 21. data entry introduces an angular deflection in the beam of EPS/(Bρ) where

$$EPS = \int B\, dZ$$

EPS is interpreted as the mean value of the bending field and DEL as the uncertainty in this mean value. This is implemented as a misalignment. If DEL is negative, then a angular misalignment of DEL/Bρ is introduced in the beam. If DEL ≥ 0, a deliberate angular misalignment of (EPS± DEL)/Bρ is introduced with the new axis used for subsequent elements.

When J = 0, EPS and DEL will be the horizontal and vertical phase space areas used with the input of Betatron functions on the beam card. In terms of the TRANSPORT σ-matrix, $EPS = \sqrt{\det(\sigma_x)}$ and $DEL = \sqrt{\det(\sigma_y)}$, where σ_x and σ_y are the 2X2 horizontal and vertical sub-matrices.

When J < 0, EPS and DEL will be interpreted as the lower and upper limit on the type of variable specified by the value of J.

Element	J	Variable
Beam	-1	All beam parameters
Pole	-2	Pole face rotation
Drift	-3	Drift distance
Bend	-4	——
——	-5	Bending magnet field
——	-6	Bending magnet field index
QUAD	-7	Quadrupole length
——	-8	Quadrupole field strength
Align	-12	X, Y, Z misalignment displacemtns
——	-13	XP, YP, ZP misalignment angles
AUX	-14	All parameters
SOL	-15	——
ROT	-16	Rotation angle

These lower and upper limits are used during computer optimization of the designated variable so as to retain physically meaningful values of the variables.

If J has a fractional part, i.e., the input is of the form 21. J.K EPS. DEL., then EPS and DEL will be the limits for the K-th variable only. i.e.,

21.	-3.2	0.	DEL.
5.01	___		
3.4	L1		
5.01	___		
3.9	L2		
5.01			
3.1			

will force the second variable (3.4, 3.9) to be constrained such that $0 \leq L1, L2 \leq DEL$. The other drift spaces would be uneffected by the 21. data card and would have their limits between the standard value of .01 and 1000.

Table 5. Standard internal limits placed on variables during optimization.

Element type	JTYPE	Type VARY code	Lower limit	Upper limit
Beam	1.	1.111111	.01	1000.
	1.		.01	1000.
	1.		.01	1000.
	1.		.01	1000.
	1.		.01	1000.
	1.		.01	1000.
Pole face	2.	2.1	-60.	60.
Drift	3.	3.1	0.1	1000.
Bend	4.	4.011	___	___
	5.		-18.	18.
	6.		-500.	500.
Quad	7.	5.11	.01	10.
	8.		-20.	20.
	9.	___	___	___
	10.		___	___
	11.		___	___
ALIGN	12.	8.111111	-1.	1.
	13.		-50.	50.
	12.		-1.	1.
	13.		-50.	50.
	12.		-1.	1.
	13.		-50.	50.
AUX	14.	14.111111	NONE	NONE
SOL	15.	19.01	NONE	NONE
ROT	16.	20.1	-360.	360.

22. X.X'. Y. Y'. dS. dP/P. β.—Particle Vectors

TRANSPORT can tract up to N_1 first order particle vectors and up to N_2 second order vectors such that $6N_1+42N_2 \leq 252$. These vectors may be initiated at several points along the beam line. Each group of vectors requires two locations in the data array and is stored in separate arrays VI(252), VC(42). The starting coordinates of the vector in the six-dimensional phase space are X, X', Y, Y', dS, and dP/P. β is the relativistic velocity (v/C) of the particle and needs only be specified if the vector is to be deflected by a particle separator (type 23 code). The units of the starting coordinates are in the same units as the beam ellipsoid (type code 1).

If $\beta \geq 2$, the vector is a second order vector. For $\beta = 2$ the second order elements of the vector are simply the square of the first order elements. If $\beta \geq 3$ then the 22. data card is followed by β pairs of numbers which specify the second order elements and values, e.g. input of XX', Xδ and XY second order terms as follows:

22. X. X'. Y. Y'. dS. dP/P. 3.
12. XX'. 16. Xδ. 13. XY.

The vector space is symmetric in second order so that $X_jX_k=X_kX_j$ with the appropriate symmetry in the R matrix. The vector input routines will automatically symmetricize the data so that in the example, only the 12., 16., and 13. elements are to be specified.

If the first order part of the second order vector is zero the vector plays the role of projecting the aberration elements of the second order transformation matrix by setting the appropriate second order term to unity. For example, if one wishes to follow the value of T(112), input:

22. 0. 0. 0. 0. 0. 0. 3.
12. 1. 0. 0. 0. 0.

The value of X. X'. Y. Y'. dS. and δp. along the beam line will then be T(112), T(212), T(312), T(412), T(512), and T(612).

If the component (8-th) entry on a vector card is negative, the card will be treated as a vector generator card, generating a group of vectors, i.e.,

22. F1. F2. DF. Q1. Q2. DQ. -FQR.

Where R is the random flag and F, Q specify the vector positions to be generated, I. E., F, Q = 1(X), 2(XP), 3(Y), 4(YP), 5(dS), 6(dP/P), where

F=F1, F1+DF, F1+2DF, ... F2.
Q=Q1, Q1+DQ, Q1+2DQ, ... Q2.

Q takes these values for each value of F. A maximum of 42 vectors may be generated. The total number, N, of vectors generated is

N=((F2-F1)/DF+1) * ((Q2-Q1)/DQ+1).

The value of the unspecified components is taken from the preceding vector card if there is one, or otherwise set to zero. The values are chosen on the grid if R is not specified. Otherwise they are chosed randomly within the area encompassed by the grid, E.G.,

```
22.  0.  0.  0.  0.  0.  0.5
22.  0.  1.5 0.25 0.  5.  1.  -12.
```

will generate 42 vectors in the horizontal phase plane with dP/P =.5 on the specified grid of points, whereas

```
22.  0   0   0   0   0   0.5
22.  0   1.5   0.25   0   5   1   -121.
```

will generate 42 vectors randomly chosen in the horizontal phase plane with dP/P=.5, such that $0 \leq X \leq 1.5$, $0 \leq XP \leq 5$.

If it is desired to know where vectors are lost, the β component may be used as a flag if the 16. 14. option is specified. This will cause $\beta = \pm L$ where L = length at which vector exceeded a horizontal aperture for $L > 0$ or a vertical aperture for $L < 0$.

The transformation for a particle vector J is

$$V_j = RV_j$$

where R is the transformation matrix of the given beam element. Unlike the phase space transformations, vector tracking is not updated by constraints. The particles to be tracked from the point of insertion to the end of the beam line. The parameters controlling the vector tracking output are the same as the beam matrix, i.e., 13. 1., 13. 2., and 13. 3. Additionally:

A 13. 25. card will terminate all ray tracing output.

A 13. 26. card will permanently override a 13. 25. suppression code

A 13. 27. card will override a 13. 25. request only at the point of occurrence.

The horizontal and vertical positions of the first six vectors will be tabulated in the "A" table, and will appear on the beam line graph.

The various vectors are labelled in the output by a number and a symbol as shown in Table 6. These symbols are used to locate the vector on any phase plots designated by the plot cards.

Table 6. Symbols corresponding to vectors used in phase space plotting.

1(A)	6(F)	11(L)	16(Q)	21(V)	26(-)	31(=)	36([)
2(B)	7(G)	12(M)	17(R)	22(W)	27(/)	32(,)	37(])
3(C)	8(H)	13(N)	18(S)	23(Y)	28())	33(0)	38(±)
4(D)	9(J)	14(O)	19(T)	24(Z)	29(()	34(*)	39(→)
5(E)	10(K)	15(P)	20(U)	25(+)	30($)	35(≡)	40(<)

Example:

```
Test ray tracking
  0
  1.   1.   2.    .35   3.   0.   0.   725.
 22.   1.   0.    .35   0.   0.   0.
 22.   0.   2.   0.     3.   0.   0.
 22.   0.   0.   0.     0.   0.   1.
 22.   0.   0.   0.     0.   0.   3.
 13.  25.                     No vector output
  3.____
  5.____
  3.____
  5.____
  3.____
 13.   27.  <------Vector output here
  3.
 22.   1.   0.    .35   0.   0.   0.
 22.   0.   2.   0.     3.   0.   0.
  4.
  3.
  5.
  3.
  5.
 13.   26.                     Vector output
  3.
  3.
  3.
 73.
```

23. L.V. A_h. A_v. βo. —Particle separator

The particle separator of TRANSPORT will deflect vectors according to their $\beta(=v/c)$. TRANSPORT follows up to 42 vectors each of which may have a different β and so may represent several simultaneous secondary beams of the same particle momentum.

A particle separator consists of a crossed B and E field which produces no deflection of particles of the correct velocity β_o but deflects particles of any other velocity β. If V is the potential on the separator plates of length L separated by an aperture A, then the angular deflection produced at the entrance and exit to the particle separator is

$$\theta = \frac{VL}{PA}\left(\frac{1}{\beta_o} - \frac{1}{\beta}\right) .$$

P is the momentum of the undeflected particle. In TRANSPORT the particle vectors have seven parameters: $x, x', y, y', s, \delta p/p, \beta$. The vector transformation for the particle

separator is then

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ s \\ \delta p/p \end{bmatrix} = \begin{bmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ & & & & & \end{bmatrix} \begin{bmatrix} x \\ x' + \theta_x \\ y \\ y' + \theta_y \\ s \\ \delta p/p \end{bmatrix} + \begin{bmatrix} 0 \\ \theta_x \\ 0 \\ \theta_y \\ 0 \\ 0 \end{bmatrix}$$

where $\theta_x = 0$, $\theta_y = \theta$ for vertical deflection and $\theta_x = \theta$, $\theta_y = 0$ for horizontal deflection.

24. J. X. Y. Z. V1. V2. — Plot Options

On-line paper plots and certain data input are provided by the type 24 element. The meaning of the parameter list X, Y, Z, V1, and V2 is selected by the value of J.

J = 0 BEAMLINE PLOT

Request a plot of the beam line and apertures to be on the output paper. X and Y are the horizontal and vertical beam plane scales and Z is the number of drift length units per print (plot) line. If Z is zero, the plot will be adjusted to be two pages in length. If X and/or Y are zero the scales will be set by the data to be plotted. In addition to the beam envelope and magnet apertures, vectors V1, V2 may be displayed where $0 \leq V2 \leq 6$, $V1 \leq V2$.

The plot may be suppressed by a 13. 2.1 entry.

J = 1 TARGET SIZE UNIT

Define the horizontal and vertical position of a rectangular target, (X_{min} = X, X_{max} = y) and (Y_{min} = Z, Y_{max} = V1). The overlap area of the target so defined with the beam acceptance polygon will be calculated during an aperture calculation (13.5. and 13.6 using option 5) to find the uniform illumination transmission and millisteradian acceptance solid angle.

J = 4 ENERGY SPECTRUM

During an energy spectrum calculation under Option 5, the aperture polygons of the section of beam line bracketted between a 13. 5. and 13. 7. data card will be calculated on momentum interval between Pmin = X to Pmax = Y in steps of dp = Z (energy interval if a 16. 18. data card is used). This card must preceed the 13. 7. data card and would normally occur at the beginning of the data deck.

J = 5 SOURCE SPACE PLOT SCALES

The horizontal polygon phase space plot scale (X, X') will be set to (X, Y) and the vertical polygon phase space scale (Y, Y') will be set to (Z, V1). This plot occurs for apertures transformed to the 13. 5. data card location. In the absence of the 24. 5. ---- data card the plots will be scaled to contain the beam phase ellipse and the polgon vertices.

J = 6 IMAGE SPACE POLYGON PLOT SCALES

Same as J = 5 except now pertains to the plots at the 13. 6. or 13. 7. data card location when these plots are activated by a 13. 30. data card.

J = F PHASE SPACE BEAM PROJECTIONS

A plot of the projection of the beam ellipsoid will be generated by this option where F specifies the phase planes to be plotted. If X and Y are non zero they will designate the scale of the plot. If they are zero the code will find the scale for the plot. If F < 0, the page eject following the plot will be suppressed.

F = 12.	XX' plot
F = 34.	YY' plot
F = 13.	XY plot
F = 16.	Xδ' plot
F = 123416.	(XY'), (YY'), (Xδ) plot's
F = 3412.	(YY'), (XX') plots on individual pages etc.

If Z and V1 are non zero they will specify a fix scale for the second of each group of two plots, e.g., 24. 123416. .360 10. 2.5 15. will plot the 12. and 16. phase plane on a scale of .36X10. and the 34 phase plane on a scale of 2.5X15. If V2 is non zero the plot scales are xmin, xmax, ymin, ymax = X, Y, Z, V1.

J = 7 PHASE PLOTS FROM A-TABLE

The 16. KLM. IJ. data cards can cause the storage of the beam or vector X, X' or Y, Y' phase points into the X-Y positions of the vector columns in the A-table. These points may be plotted by giving

24. 9. VEC. X1. X2. Y1. Y2.

where VEC is the vector number whose X-Y positions are to be plotted and X1, X2, Y1 and Y2 are the X-Y scale minima and maxima if given. Should X1 = X2 = Y2 = Y2 = 0, the code will find the necessary scale.

25. MA. INTYPE. PARM. — Calculated Matrix

The 25. element will accomodate the input of first and/or second order transfer matrices without filling the data array. Alternatively, TRANSPORT can calculate the matrix and then used it without the necessity of recalculation, saving much computer time in some cases. The matrices readin or calculated and subsequently stored via the 25 element can cross from one data case to the next provided that the momentum and units are not changed from one data

case to the next.

On first order TRANSPORT's provision is made for up to 15 matrices to be read or calculated and saved for use in the current data case or any subsequent data case depending on if INTYPE is positive, negative or zero. If INTYPE is positive the matrices are readin from the input file. If INTYPE is negative the RC, RC2, RTN or R matrices will be saved according to if INTYPE is -1, -2, -3, or -4 respectively. In second order only the RC matrix can be saved, so INTYPE should always be -1 or 0.

```
25. NAME.  INTYPE.  T2ND.
```

The matrices saved under name NAME will be used as the R-matrix whenever a data card of the form

```
25.  NAME.   0.   0.
```

is encountered. Since only 15 such names are allowed in first order and four such names in second order, provision is made to reset the matrix storage pointer via a

```
25.   0.   0.   0.
```

data entry. 15 new matrices can then be saved, or four new matrices in second order.

When INTYPE is greater than zero, a matrix will be readin from the input file. The first order part of the matrix is readin row-wise, INTYPE/10 rows which will be stores in a special array under the name NAME. The matrix so read will be applied as a transformation at this point in the beam line as well as at any location where a 25. NAME 0. 0. data card appears. As an example, consider the input of the first four rows of a matrix (first order) with name KRUD. The data would be:

```
25.  KRUD.   40.    0.                                  $ INPUT 40/10 ROWS.
      1.99   3.44   0    0     0      .234              $ ROW 1
     -2.43  -3.708  0    0     0     1.674              $ ROW 2
      0      0     -1.676   -.527    0     0            $ ROW 3
      0      0     -3.438  -1.678    0     0            $ ROW 4
```

The length associated with this matrix can be specified by a preceding 16. 17. length card. This matrix will be used in the calculation of the beam line at the location of the

```
25. KRUD 40.  0.
```

data card and any location where a card of the form

```
25. KRUD  0.  0.
```

is encountered.

When INTYPE is negative, a matrix calculated by TRANSPORT is saved under the name specified. As an example the following two data sets will produce the same matrix transformations:

```
9. 4.                          6. 0. 1. $ UPDATE RC MATRIX
3. 1.5                         3. 1.5
4. .75  11.6  0.               4. .75  11.6  0.
2. 12.                         2. 12.
3. 2.0                         3. 2.0
9. 0.                          25.  SAVE -1.   $ SAVE =RC MATRIX
-                              25.  SAVE  0.   $ USE SAVE
-                              25.  SAVE  0.   $ USE SAVE
-                              25.  SAVE  0.   $ USE SAVE
```

In first order cases with INTYPE = -1, the inverse matrix will be stored when T2ND = -1 or the reflection matrix will be stored when T2ND = -2.

The 25. element can also be used in second order for the insertion of an arbitrary first and second order transfer matrix into the beam line calculations. This facilitates the calculation of real beam lines which use numerically calculated second order matrices.[7] Up to four different second order matrices can be accommodated each displacing only four locations in the normal data array. These matrices are stored in separate arrays and each may be referenced in the data array in more than one location.

The vector space used by TRANSPORT is 42 dimensional with six values specifying the first order components

$$x = (x,\ x',\ y,\ y',\ s,\ \delta p/p).$$

There are 36 second order components ($x_j x_k$, $j = 1, 6$, $k = 1, 6$). The expansion of x_i through second order in the initial condition is

$$x_i = \sum_{j=1}^{6} R_{ij} x_j + \sum_{j=1}^{6} \sum_{k=1}^{6} T_{ijk} x_j x_k .$$

There are only 21 unique second order T elements for each i since $x_j x_k = x_k x_j$. Then a complete matrix is specified by the 36 first order R_{jk} elements and the 126 second order T_{ijk} elements. It should be noted that $(x_j x_k)$ contributes $2T_{ijk}$ to x_i since $T_{ijk} = T_{ikj}$.

SECOND ORDER, INTYPE = NM.

N gives the first order matrix input information and M gives the second order matrix input information; i.e.,
The ten's position gives the number of rows of the first order transfer matrix to be read. The units position gives the type of second order matrix input to be used. e.g., if INTYPE = NM., then M = 1 specifies the reading of PARM pairs of numbers, (ijk, T_{ijk}) while M = 2 specifies the reading of all 21 T_{ijk} matrix elements for the i's given by PARM. If PARM = 12346., then the input will consist of the 21 numbers (T_{1jk}, k = 1, 6, J = 1, k), the 21 numbers (T_{2jk}, k = 1, 6, J = 1, k)..... (T_{6jk}, k = 1, 6, J = 1, k). If INTYPE = 0, no matrix is read, but the matrix stored previously in array name is inserted into the calculations.

<u>Examples:</u>

Input of first order matrix only in array 3._____	25. 3. 60. 0. Six data cards follow 1 for each row
Input of first 4 rows of first order matrix only into array 2._____	25. 2. 40. 0. Four data card follow
Input of T_{111}, T_{112}, T_{211}, and T_{316} into second order matrix at location 1 _____	25. 1. 1. 5. 2 data cards follow

Input of entire second order matrix coefficients for x, x and s. (1, 2, and 5).	25. 2. 2. 125. 18 data cards follow 6 for X, 6 for X and 6 for dS.
Input of entire first and second order matrix into location 4	25. 4. 62. 123456 42 data cards
Store and use first and second order matrix KRU	25. KRU. -1. 0. $ Store 25. KRU 0. 0. $ Use

Example data

```
Beam line with two different arbitrary second order matrices
0
1.  2.54  10.  2.54  10.  0.  0.  1.39
3.  1.
5.  .75  7.4  15.
3.  1.
17.  1.   0.   3.
25.  1.   41.  10.
```

$R_{11.}$ $R_{12.}$ $R_{13.}$ $R_{14.}$ $R_{15.}$ $R_{16.}$
$R_{21.}$ $R_{22.}$ $R_{23.}$ $R_{24.}$ $R_{25.}$ $R_{26.}$
$R_{31.}$ $R_{32.}$ $R_{33.}$ $R_{34.}$ $R_{35.}$ $R_{36.}$
$R_{41.}$ $R_{42.}$ $R_{43.}$ $R_{44.}$ $R_{45.}$ $R_{46.}$

} 1st 4 rows of 1st order transfer matrix

113. T(113). 114. T(114). 116. T(116). 123. T(123).
211. T(211). 236. T(236). 312. T(312). 336. T(336).
411. T(411). 436. T(436).

} 10 pairs of 2nd order matrix demands

```
3.  10.
5.  .75  -3.5  15.
3.  1.
25.  2.   42.   13.
```

$R_{11.}$ $R_{12.}$ $R_{13.}$ $R_{14.}$ $R_{15.}$ $R_{16.}$
$R_{21.}$ --- --- --- --- ---
$R_{31.}$ --- --- --- --- ---
$R_{41.}$ --- --- --- --- ---

} 1st 4 rows of 1st order matrix

T(111).
T(112). T(122).
T(113). T(123). T(133).
T(114). T(124). T(134). T(144).
T(115). T(125). T(135). T(145). T(155).
T(116). T(126). T(136). T(146). T(156). T(166).

} i = 1 second order submatrix T_{1jk}

T(311).
T(312). T(322).
T(313). T(323). T(333).
T(314). T(324). T(334). T(344).
T(315). T(325). T(335). T(345). T(355).
T(316). T(326). T(336). T(346). T(356). T(366).

} i = 3 second order submatrix T_{3jk}

```
3.  5.
13.  4.
73.
```

Example of beam line with one 2nd order matrix at 2 locations

```
0
1.   2.54   10.    2.54   10.    0.    0.    13.9
3.   1.
5.   .75    7.4    15.
3.   1.5
17.  1.     0.      3.
25.  1.     42.    12.

R11.  R12.  R13.  R14.  R15.  R16.
R21.  ---   ---   ---   ---   ---
R31.  ---   ---   ---   ---   ---
R41.  ---   ---   ---   ---   ---

T(111).
T(112).   T(122).
T(113).   T(123).   T(133).
T(114).   T(124).   T(134).   T(144).
T(115).   T(125).   T(135).   T(145).   T(155).
T(116).   T(126).   T(136).   T(146).   T(156).   T(166).

T(211).
T(212).    ---
T(213).    ---      ---
T(214).    ---      ---      ---
T(215).    ---      ---      ---      ---
T(216).   T(216).   T(236)   T(246).   T(256).   T(266).

3.   7.
5.   .75    -5.    15.
3.   2.
25.  1.      0.     0.
3.   4.
13.  4.
73.
```

INPUT of 1st and 2nd order matrices in array 1.

Repeat matrix stored in array 1. at this location.

26. DL. AMPS. PRTFQ. RFFRE. Space Charge

The space charge type card will cause the type 3, 4, 5, and 19 elements (drift spaces, bending magnets, quadrupoles and solenoids) to be divided into sub-lengths DL and any remainder with a space charge impulse applied at the end of each sub-length. Either a two or three dimensional model can be used by setting the rf frequency to zero for the two dimensional model (D.C. beam) or to the beam pulse frequency for a three dimensional model (pulse beam with length given by the seventh parameter on the beam card). The data input parameters are:

DL = distance interval at which space charge impulse will be applied

AMPS = applied current of beam in amperes

PRTFQ. = print frequency in units of DL

RFFRE = rf bunch frequency in MHz

When using space charge the mass of the beam particles must be specified via a 16. 3. SM data entry in units of electron mass (units 10).

The space charge impulse is calculated from the electric field of the elliptical charge distribution given by the beam sigma matrix. The space charge calculation effects all transformations; the beam, and vectors, and the R, RC, and RC2 transformations. The transformations are:

$$R_{SC} = \pi R_j E_j$$

$$\sigma = R_{SC} \sigma_O R_{SC}^T$$

$$RC = R_{SC} RC$$

$$V = R_{SC} V_0$$

$$RC2 = R_{SC} RC2$$

Here, R_j is the transformation matrix for the sub-length, E_j is the electric field matrix for space charge forces, and R_{SC} is the accumulated transformation matrix for the element.

27. L. V. RFPHSE. RFFREQ. — RF Buncher

The rf buncher introduces a focusing term in the horizontal and vertical phase space from the rf field and a dependence of momentum spread on longitudinal position within the bunch. The energy spread in the bunch is assumed linear. The transformation matrix for the rf buncher is given below.

L	=	Length of buncher, must be zero
V	=	rf voltage in mega-volt's
RFPHASE	=	rf phase, must be either 0 or 180 degrees
RFFREQ	=	rf frequency in mega-Herzt.

$$R = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -\lambda/2\gamma^2 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -\lambda/2\gamma^2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \lambda & 1 \end{bmatrix}$$

where

$$\lambda = \frac{2\pi \cos\ (\mathrm{RFPHASE}).\ V\ .\ \mathrm{RFFREQ}}{\alpha \cdot \mathrm{sm} \cdot \gamma \cdot \beta^3}$$

$$\alpha = \frac{e}{m_e c^3} = 15350.0$$

$$\gamma = (1-\beta^2)^{-1/2}$$

β = relativistic velocity, V/c

SM = mass of particle in units of electron mass.

Section 3 - Modification of Data

OPTIONS

The first data card in every TRANSPORT data case is a title card and the second data card in every TRANSPORT data case is an option card that specifies the type of deck that follows. If the first option is greater than 0 in a given data case, then more than one option card may appear in that data case with the case always ending in an Option 0. Remember that an Option 0 ends with a 73. data card as the last card in the data case. Consider a data deck in which the Option 0 data has already been processed and the next case is as follows:

Example	Title card
1	Option card
1. X. XP. Y.....	Beam card
22. X. XP. Y.....	Vector
2	Option card
37. -10.	Option 2 data
44. -10.	Option 2 data
0	Option card (may be blank)
73.	Option 0 terminator.

The Option 0 data which comprises the basic TRANSPORT data deck has already been extensively discussed. I will now examine the options that modify this basic data.

OPTION 1 Data Input

Option 1 allows the input of new particle data to be transformed by the existing beam line. Option 1 only allows beam data (type 1), axis shift data (type 7) beam correlation data (type 12) and particle vector data (type 22) input. The data replaces the 1, 7, 12, or 22 data in the original data deck and the run is repeated if Option 1 is terminated by Option 0 (see Examples 1 and 2 below). If the option is terminated in a second order TRANSPORT by Option 4 the data will be transformed to the end of the beam line by the existing RC matrix and a phase plot produced if a phase plot card (24. 123416., etc.) existed in the original data deck (see Example 3 below).

Example 1, Option 1, 0

```
  1
  1. X. XP. Y. YP. S. DP. P.
 22. X. XP. Y. YP. S. DP. C.
  0
 73.
```

Example 2, Option 1, 2, 0

```
  1
  1. X. XP. Y. YP. S. DP. P.
 12. XXP. 0. 0. 0. 0. YYP. 0.
  0. 0.  SX. 0. 0. 0. 0. 0.
 22. X. XP. Y. YP. S. DP. C.
  2
143. -10.
  0
 73.
```

```
Example 3, Option 1, 4, 0
   1
   1. X. XP. Y. YP. S. DP. P.
  22. X. XP. Y. YP. S. DP. C.
   4
   0
  73.
```

A beam line may be continued via the Option 1 with a negative beam card. This will cause the beam card, correlation card and vectors if present in the data array to be updated with the terminal values from the previous case. When execution is then attempted, the vectors and beam will be continued without being re-initialized so that the beam line is continued from the previous case. Consider running 200 revolutions in an accelerator whose single-turn matrix has previously been calculated and stored under the name FULLT.

```
RUN TURNS 1 - 100
 0
16.  216 11 $ STORE VECTOR 1 X as VEC 2-X
16.  236 22 $ STORE VECTOR 1 XP as VEC 2-Y
 1.   1. 3.3 .7 6.4 0. 0. 5.
22.   1. 0. 0. 0. 0. 0. 2.
12.   OR15
17.   1. 0. 3.
 9.   100.
25.  FULLT 0. 0.
13.   1.
 9.   0.
24.   7. 2. $ phase plot VEC 2, i.e., VEC 1 X-XP
73.
RUN TURNS 101-200
 1
-1  $ Beam card with type code = -1., continues beam.
 0
73.
```

The division into two runs of 100 TURNS each is necessary because the A-table can accommodate only 99 entries. Note that no harm is done by overflowing the table as in the previous example; 100 turns will lose the plot and table entry number 100 and 200.

OPTION 2

Option 2 allows the alteration of the data as left by the preceding data deck. Changes of a single data element may be made by reading the value of the index counter of the data to be changed followed by the chance, or by using special control cards such as

ALTER	- Alter one or more data elements.
ALINE	- Add a line to the data.
DLINE	- Delete a line from the data.
FIX	- Fix the variable and remove the constraints.
MOVE	- Move one or more data lines.
NAME	- Re-name the data.
PUNCH	- Write the data array out on tape 7.
REVERSE	- Reverse data order in array.
REFLECT	- Change sign of vector X' and Y'.
BETAF	- Betatron Function generator.

The reading of these cards and the modification they produce to the data deck continues until a new option card is encountered. This causes initiation of the new option. Finally, the data case is terminated by a blank card (option = 0) and resumption of standard (option 0) data input occurs.

Inorder to better understand how the Option 2 control cards operate on the data, I will describe the naming procedure for the data array and then give a detailed account of the use of Option 2 control cards.

Data Array and Names

The data appearing between the option card and the sentinel card (or 73. card) serially fills a singly dimensioned data array, with each number specified, located in the data array at position given by the data array counter, I. The data may subsequently be altered by reference to it by its I count value. Alternatively, each data input card may be given a name (if not explicitly by the user, the code will generate a unique name for each data card) which then can be used to alter or refer to the various parameters of that line in the data array. The names are restricted to six or less alphameric characters, the first of which must be alphabetic.

For each name there corresponds an I, the I of the type code. The data is stored in the data array in the order the cards are read in consequently the names are in that order also. In this report, we will often refer to name pairs (e.g., NAME 1, NAME 2) where NAME 1 must refer to a smaller or equal I count than NAME 2, that is, the data line for NAME 1 preceeds the data line for NAME 2 or NAME 1 equals NAME 2. We will also often refer to index pairs (e.g., I 1, I 2) where I1 must be less than or equal to I 2. Names and I counts may be mixed, i.e., NAME 1, NAME 2 could be replaced by NAME 1, I 2 where I 2 is the index counter value of NAME 2.

More than one data line may have the same name. The advantage of this is that all these cards can be changed, deleted, etc., together by the ALTER, ALINE and DLINE operations, referencing that respective name.

The standard name generation of TRANSPORT is shown below. The names will be generated by the type of data element and an incremental counter appended, i.e., Q1, Q2, Q3, etc. for quadrupoles, name Q. These names will be unique and may be used with the ALINE, ALTER, DLINE and MOVE operations.

Standard name	Type	Meaning of Card
BEAM	1.000000	BEAM CARDS
FF	2.0	FRINGING FIELD TO BENDING MAGNET
L	3.0	DRIFT SPACE
BM	4.000	BENDING MAGNET
Q	5.00	QUADRUPOLE
SLIT	6.	SLITS
AXIS	7.	AXIS CARDS
ALIN	8.000000	ALIGNMENTS CARDS
REP	9.	REPEAT CARDS
CON	10.0	CONSTRAINT CARDS
ACC	11.	ACCELERATOR CARD
TIL	12.	PHASE SPACE TILTS
IO	13.	INPUT-OUTPUT CARDS
AUX	14.000000	AUXILIARY MATRIX
UNIT	15.	UNIT CHANGE CARD
DA	16.	PARAMETER CARD
SEC	17.	SECOND ORDER
SEX	18.	SEXTUPOLE
SOL	19.00	SOLENOID
STRY	21.	STRAY FIELD

VEC	22.	VECTORS
SEP	23.	PARTICLE SEPARATOR
PLOT	24.	PLOT CARD
MAT	25.	MATRIX INPUT CARD
SC	26.	SPACE CHARGE
BUN	27.	BUNCHER

Names and Duplicate Names. If two or more data lines have identical names, they will be altered or deleted together. The ALINE option used with a duplicate name data will insert the new line after each appearance of the name in the data deck. To alter the J-th position of the N-th multiple named data line requires the input of N and J after the name, i.e.,

ALTER, NAME, N, J. CHANGE.

To add the new line after the N-th occurrence of the multipally named data only, N must be specified after the name, e.g., to add a 13. 1. line after the second QUADH data line, one would use

ALINE, QUADH, 2, 13. 1.

If only the N-th multiply name line is to be deleted, N follows the Name, e.g., to delete the second quadrupole QUADH one would enter

DLINE, QUADH, 2 .

It is not possible to use a multiply-named data element as one parameter of a multiple delete, i.e., the following card is illegal:

DLINE, QUADH, I03,

if either QUADH or I03 are multy named data.

ALINE or AL. The ALINE (add line) option allows the user to add new data lines and elements to his data array during Option 2. The entries consist of the location or name of the line after which the new line is to be added, followed by the new line. Example: consider adding a 13. 1. data line after a drift with name DRFT 4 which occurs with an index value of 29 in the date array. This can be accomplished by one of the following entries:

ALINE, 29, 13. 1.
ALINE, 29, 13. 1. NAMEX
ALINE, DRFT 4, 13. 1.
ALINE, DRFT 4, 13. 1. NAMEX

If the name NAMEX of the new data line is not entered, the code will generate a unique name for the new data line.

ALTER or A. The ALTER option allows the user to change or alter any element in his data array. There are two general schemes that can be employed, one uses the location of the element to be changed by designation of the storage index I, within the data array, the other uses the unique name of the data line and the location of the element to be changed within this line. Example, consider changing the field strength of the first quadrupole with name QV to -8.75 KG. This quadrupole occupies, say, location 19 through 22 in the data array and has name QV. The alteration can be accomplished by any of the equivalent entries.

```
ALTER, 21, -8.75
ALTER, QV, 3, -8.75
ALTER, QV, 1, 3, -8.75
```

The general scheme is

ALTER, NAME, N, J, CHANGE.

where NAME is the name of the data line, N would only be needed if more than one data line has this name. J is the position on this line for the change. If more than one consecutive change is to be made on this data line, these changes may be entered together. Consider changing the length and field of a quadrupole QV to 0.75M and -13.65 kG; the entry could be

ALTER, QV, 2, 0.75, -13.65

DLINE or D. The DLINE (delete line) option allows the user to remove a data line from his data array. A group of lines may be removed together by specifying the name or index of the first line and the last line, bracketing all lines to be removed.

```
DLINE, I
DLINE, NAME
DLINE, I 1, I 2
DLINE, NAME 1, NAME 2
DLINE, NAME 1, N1, NAME 2, N2
ETC.
```

FIX. The FIX option removes variables in the data array by zeroing the vary codes of each type code and negating all constraints. The fix option will operate on the entire data set if no delimiters are given, otherwise it will operate from NAME 1 to NAME 2 only.

```
FIX, NAME 1, NAME 2
FIX
```

The fix option operating on the data shown in column 1 produces the result shown in column 2. It operates on all the data in the data array.

1. _____	1. _____
5.02 _____	5. _____
3. _____	3. _____
5.01 _____	5. _____
3. _____	3. _____
10.1 _____	-10.1 _____
10.2 _____	-10.2 _____
3. _____	3. _____
10. _____	-10. _____

NAME. The NAME option allows the user to rename his data array with the standard name convention internally generated by the code. The entry would be,

NAME.

If only one name is to be changed it may be done by entering

NAME, NAME, NEWNAME.

If a string of names are to be changed, then the string is entered, ending in the new name for the string, e.g., if L1, L5, L6, L22, and the 2nd occurrence of the multipally named drift LL are to be given the name LX, the entry would be

NAME, L1, LL, 2, L5, L6, L22, LX

Should one wish to assign unique names to several multi-named data elements. He enters the list of NEWNAMES, and/or occurrence number ending the list with the old name followed by an *. For example, say one wished to change the 1st, 2nd, 5th, 6th, and 22nd occurrence of the data named LX to LD1, LD2, LD5, LD6, and LD22, then the entry would be

NAME, LD1, LD2, 5, LD5, LD6, 22, LD22, LX *

MOVE. This option allows the user to move a group of data within the data array

MOVE, NAME 1, NAME 2, NAME 3.

Here the data lines NAME 1 to NAME 2 are moved to follow NAME 3. If only one data line is to be moved the entry would be

MOVE, NAME 1, NAME 3.

POLYGON. The POLYGON entry in Option 2 will set OPTION=POLYGON and initiate the polygon calculation as explained elsewhere.

PUNCH-PUNCH, X-PUNCH, COMMENTS FIELD. The PUNCH card included in the Option 2 deck will cause the data array to be written to tape 7 in field free format with data names appended. If there is a second non-blank entry on the punch card, tape 7 will be written in 8F10. Format without names. In either case the data on tape 7 may be used as input to transport on subsequent runs. If a third entry is made on the punch card, the entry will generate a comment card which will precede the title card of the data case punched. e.g. PUNCH,, this comment will precede the title card. The comment will automatically start with a $ so as to be properly read by the field free input routine of TRANSPORT.

REVERSE, NAME 1, NAME 2. The REVERSE option allows the user to reverse the data entries from NAME 1 to NAME 2. This is particularly useful when wanting to run the beam backwards or to make a symmetric data case with the pull option. The effect of entry of reverse Q1, Q2 will be the following:

Original data	Effect of Reverse	Comments
1R8	1R8	First data card
3 1.25	3.125	Second data card
5 .5 6.2 4 Q1	5 .5 -3.6 4 Q2	Note Q2 is first
3 .5 L2	3 .5 L2	
5 .5 -3.6 4 Q2	5 .5 6.2 4 Q1	Note Q1 is last
3 1.75 L3	3 1.75 L3	
13 4	13 4	
SENTINEL	SENTINEL	END CASE

Some care must be used if the order of the data is important when using the reverse procedure. For example, the apertures of the bending magnets must precede the bending magnet card.

Consider the following example of a quadrupole doublet constrained to produce first a focus and then a waist. After solving for the waist the beam line is continued by adding a bending

magnet and a new quadrupole.

BEAM FOCUS

```
0
1. ________
3. ________
5.01_______ -------I count for 5.01 is 11
3. ________
5.01_______ -------I count for 5.01 is 17
3. ________
10. -1. 2. 0. .001_________I count for -1. is 24 and 25 for 2.
10. -3. 4. 0. .001_________I count for -3. is 29 and 30 for 4.
73.
Beam waist
2
24.  2.
25.  1.
ALTER, CON2, 2, 4, 3
--------------------------Blank card
73.
Add rest of beam line
2
FIX
--------------------------Blank card
3. ________
4. ________
3. ________
5.01_______
5.01_______
3. ________
10._________
10._________
73._________
```

REFLECT. When one wishes to run his beam line backwards, the signs of the vector divergences must be changed. The REFLECT option accomplishes this, taking $x' = -x'$ and $y' = -y'$

BETAF. The betatron function at the end of a lattice supper period can be calculated by entry of a card under Option 2 of the form

BETAF N

where the betatron functions will be calculated from the RC matrix if N=4, the RC2 matrix if N=2 or the R3 matrix if N=3. The beam card data will be automatically replaced by

$$1. \quad \beta_x \quad 0. \quad \beta_y \quad 0. \; - - -$$

$$\beta_x = M_{12} / \sqrt{1 - M_{11}^2}$$

$$\beta_y = M_{34} / \sqrt{1 - M_{33}^2}$$

$$\alpha_x = \alpha_y = 0.$$

The off-energy function will also be calculated if an axis shift data card follows the beam card. In this case, the beam centroid play the part of the dispersion function with the values set as

$$7. \quad \eta \quad \eta' \quad 0 \quad 0 \quad 0 \quad 1.$$

where

$$\eta = M_{16}/1 - M_{11}$$

$$\eta' = 0.$$

An output table will be generated giving the values of

$$\beta_x, \ \gamma_x, \ \alpha_x, \ \eta_x, \ \eta_x', \ \beta_y, \ \gamma_y, \ \alpha_y, \ \mu_x, \ \text{and} \ \mu_y.$$

Also, the transition gamma will be calculated.

OPTION 3 Data Input

The TRANSPORT option 3 provides the user with the ability to cycle from one to four data elements over a range of values. If variables are present in the Option 0 data deck and are not being cycled, they will be restored to their original value at the start of each run.

The total number, N, of transport runs that will be generated by the Option 3 data is

$$N = N_1 N_2 N_3 N_4 + \text{NOPTIM}$$

where

$$N_j = (V_{j2} - V_{j1})/DV_j + 1 \qquad J = 1, 2, 3, 4$$

and NOPTIM is the number of subsequent runs at optimum starting values. The variables J are cycled between V_{j1} and V_{j2} in steps of DV_j. Care must be exercised not to specify DV to small for the number of runs generated will become exceedingly large. Furthermore, in order to reduce execution time it is recommended that only essential data cards be present in the Option 0 data that the Option 3 data is working on.

The data input for TRANSPORT consists of a series of data decks beginning with a title card, option card, and ending with a 73 card–the data between the option card and the 73 card is chosen from various possible elements which describe the beam line. This data serially fills a singly dimensioned data array, with each number specified, located in the data array at position given by the I counter. If a user wishes to change a data element, he must specify the value of

the I counter (i.e., location of data) for the element in the data array. If the data deck has been previously run, TRANSPORT gives the I of the type code specifying the data element as normal output. The Option 3 data operates on the data in the data array as established by the preceding data deck or decks, and consists of a series of one or more cards specifying up to eight parameters per card whose meaning will now be explained.

Title card typical data deck:

3

K.J	V1.	V2.	DV.	RANDOM.	NOPTIM.	V6.	V7	
.	.	.	.	.	.	.	.	MAXIMUM of 4 such cards.
.	.	.	.	.	.	.	.	
.	.	.	.	.	.	.	.	

73.

K > 0	K specifies which variable is to be cycled i.e., K = 1 means first variable, K = 2 means second variable, etc. If Random=0 the variable will be assigned values between V1 and V2 in steps DV. If RANDOM ≠ 0 the variable will be assigned a total of DV values scaled to lie between V1 and V2. The random number generator is started at a point determined by the value of random. NOPTIM specifies how many subsequent optimization runs shall be made using the NOPTIM best starting conditions found (smallest RMS deviation), the largest of the NOPTIM less than 11 encountered in each data set will be used. V6 and V7 are not used when K > 0.
K< 0, J = 0(e.g. -21.0)	K specifies the I of the data in the data array where I =-K. The rest of the data is the same as above for K > 0 where the parameter Data(I) is assigned values V1 to V2 in steps of DV or assigned DV random values between V1 and V2.
K< 0, J = 1(e.g. -21.1)	Each data element with J =1 will be assigned values together so that a total number of (V2-V1)/dV+1. cases will be generated even though more than one data element is being changed. This type of option will move two quadrupoles along a given line in the variable space as opposed to a grid of values.
K< 0, J = 2(e.g. -21.2)	Each data element with J = 2 will be assigned the values specified on the remainder of the card until no more nonzero values are found, i.e.; data element K will assume values V1, V2, dV, RANDOM... V7 until subsequent data fields on the card are all zero.

If the data being cycled is accompanied by NOPTIM ≠ 0 the output will consist of a single line giving the RMS deviation for the fit to the constrained quantities, the value of the variables used, and the actual value of the constrained parameters for each set of values chosen. No optimization is performed. After completion of the cycling of the data, NOPTIM optimization runs will be performed using the values of the variable giving the NOPTIM smallest RMS deviations as starting conditions in order to obtain optimum fits. If NOPTIM=0 normal transport output is obtained for each set of cycled variables including optimization if appropriate.

When using Option 3, the first entry on a card may also be a data name. In this case, the second entry will be the location of that named line for which the data applies. The third and subsequent entries are the same as previously described. In the J = 1 or J = 2 type entries are to be made, J is appended to the location. For example, consider a quadrupole by the name QQ whose field (third entry on quadrupole card) is to be assigned the 4 values given on the Option 3 card (J = 2).

QQ 3.2 -10.27 -11.65 -12.076 -14.3.

The second number is LOC.J while entries 3-6 are the field values. If the named data is multi-named, i.e., more than one data line has that name, it is mandatory that the occurence number follow the name. The location entry and Option 3 parameters being displaced to positions 3, 4 . . . etc. Consider cycling the length of drift for the 6-th data line by the name LSEP over the values 2.6 to 10.6 in steps of 1. The entry would be

LSEP 6 2.0 2.6 10.6 1. 0. 4.

The general scheme used is

NAME	LOC.J	V1	V2.	DV.	RANDOM.	NOPTIM.	V6.	V7.
NAME	OCCURRENCE LOC.J	V1.	V2.	DV.	RANDOM.	NOPTIM.	V6.	V7.

where OCCURRENCE is the mandatory multi-named occurrence number.

Examples

Several examples are in order. All examples will operate on the basic data deck given in Example 1 consisting of a bending magnet followed by a quadrupole doublet. We attempt to discover the quadrupole fields required to produce waist to waist transformations. Example 2 shows the data required to cycle the two quadrupoles over a uniform grid of values shown in Fig. 7. The Example 3 data would produce a random selection of quadrupole fields in one octant of the grid.

Often a person wishes to examine the effect on a beam line when two or more elements move in a correlated way. Thus consider Fig. 7 where the two quadrupoles are to have equal values but opposite polarity. Example 4, will step both quadrupoles along a diagonal line within this grid. A set of data elements may be assigned specific values as in Example 5. Here the data deck of example one is modified by fixing the first quadrupole doublet (5.01 → 5.0 for data elements 20 and 26) and removing the constraints for this doublet (10→ -10 for data elements 32 and 37). To this modified deck is then added a quadrupole triplet and a new double waist constraint. This data deck is then acted upon by the Option 3 deck following it which cycles the triplet over one octant for each of the quadrupole doublet field values found previously giving waist-waist transformations.

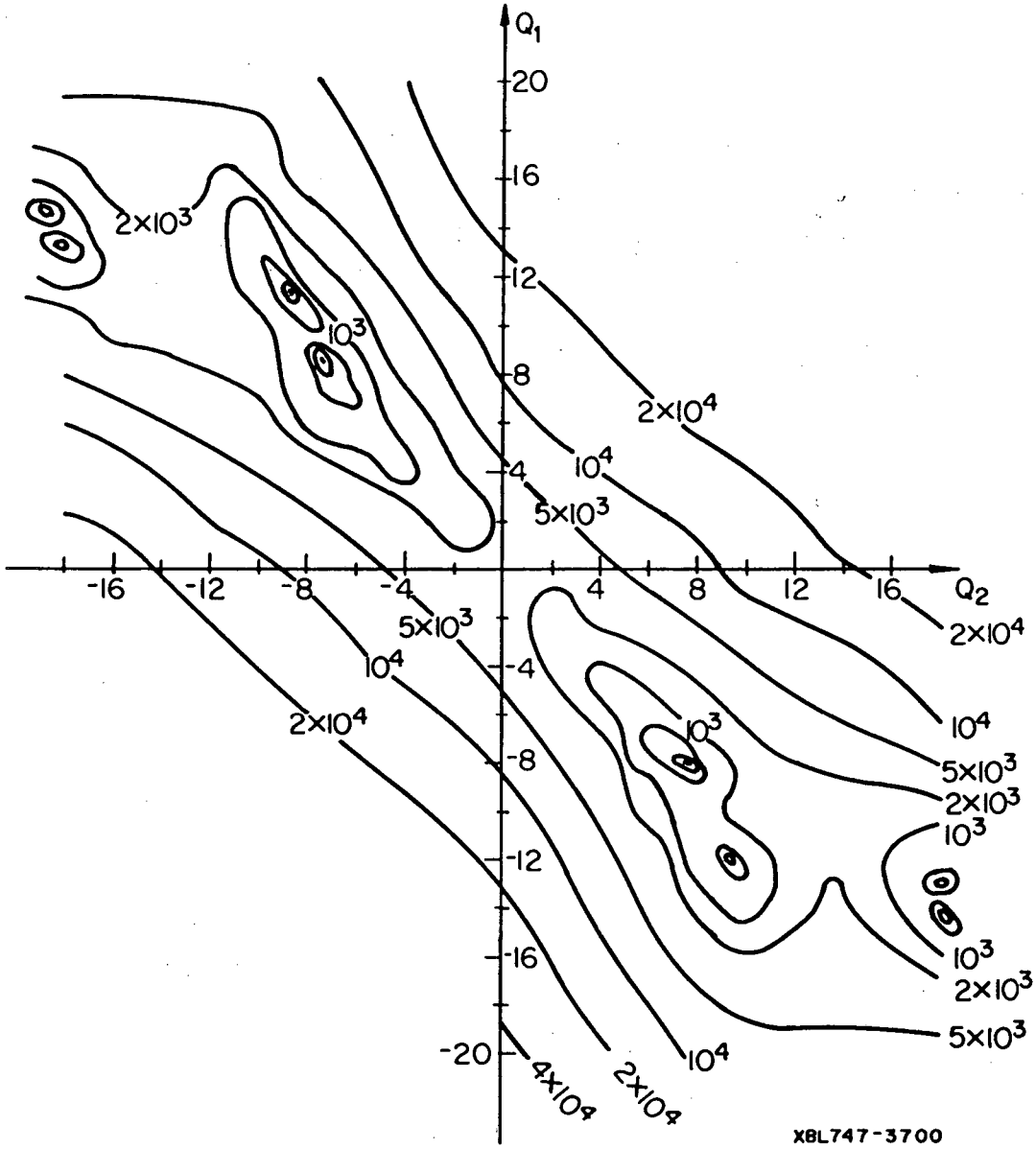


Fig. 7. ISO-chi square contours for two quadrupole waist to waist search showing regions of four solutions of different magnification.

EXAMPLE 1:

```
July 14, 1970

1.
UNIT CHANGE
0
15.          4.
15.          1.      IN      2.54
15.          2.      MR      1.
15.          6.      PC      1.
15.          8.      IN      .0254
73
BASIC DATA DEK (BM/QUAD/QUAD/DOUBLE WAIST)
0
1.           .3      8.      .3      8.      0.      0.      1.3
13.          2.
4.           15.     1.48    0.
2.           2.75    0.
3            138.5
5.01         16.     -10.    4.
3.           8.
5.01         16.     -10.    4.
3.           48.
10.          2.      1.      0.      .01
10.          4.      3.      0.      .01
-10.         -1.     2.      0.      .001
-10.         -3.     4.      0.      .001
13.          1.
13.          4.
73.
```

EXAMPLE 2:

```
OPTION 3 WAIST, EXAMPLE 1
3
1.           -20.    0.      2.      0.      4.
2.           0.      20.     2.      0.
Blank
73.

OPTION WAIST
3
1.           0.      20.     1.      0.      10.
2.           -20.    0.      1.
Blank
73.
```

EXAMPLE 3:

```
RANDOM NUMBERS, EXAMPLE 2
3
1.           -20.    0.      11.     1.      4.
2.           0.      20.     11.     1.
Blank
73.
```

EXAMPLE 4:

```
3
-22.1        0       -20.    -2.     0.      4.
-28.1        0.       20.    2.
Blank
73.
```

EXAMPLE 5:

MODIFY BASIC DATA DECK BY ADDING TRIPLET AND FIXING FIRST QUAD

```
2
20.          5.
26.          5.
32.          -10.
37.          -10.
Blank card
3.           48.
5.02         16.      5.       4.
3.           8.
5.01         32.      -5.      4.
3.           8.
5.02         16.      5.       4.
3.           64.
10.          2.       1.       0.       .01
10.          4.       3.       0.       .01
13.          1.
13.          4.
73.
```

SEARCH TRIPLET AT EACH OF 4 MAGNIFICATIONS FOUND FOR FIRST QUADRUPOLE

```
3
1.           0.       20.      5.       0.       5.
2.           -20.     0.       5.
-22.2        -8.38    -11.85   -13.43   -14.41
-28.2        7.26     8.69     13.25    18.62
Blank
73.
```

SEARCH

```
 1     13.000000     -2.000000
 3      1.010100       .200000     11.000000      .100000     -13.000000
11     22.000000      8.000000
13     24.000000      0.          10.000000    10.000000        0.
20      3.000000      2.000000
22      5.000000     30.000000     10.670000     6.000000
28      3.000000      8.100000
30      2.000000      5.000000     -0.
33      4.000000     44.130000     11.447000    -0.
37      2.000000     40.000000     -0.
40     13.000000      1.000000
42      3.000000     17.770000
44      5.010000     20.000000     -3.251914     4.000000
48      3.000000      7.000000
50      5.010000     30.000000      6.494160     6.000000
54      3.000000     27.050000
56     10.000000      1.000000      1.000000     5.000000          .050000
61     10.000000      3.000000      3.000000     1.800000          .018000
66     23.000000   -120.000000       .560000     6.000000         2.000000
73     10.000000      1.000000      1.000000     5.000000          .050000
78     10.000000      3.000000      3.000000     1.800000          .018000
83      3.000000     22.550000
85     10.000000     -3.000000      4.000000     0.                .001000
90     10.000000     -1.000000      2.000000     0.                .001000
95     13.000000      4.000000
97     13.000000      1.000000
```

OPTION 4

Option 4 is available on second order TRANSPORT and transforms the vectors and beam existing in the data array using the last value of the accumulated transformation matrix, RC. The usefulness of Option 4 is apparent during second order runs where many vectors are to be transformed in order to investigate the second order nonlinearities of the beam line. Use of the Option 4 results in considerable saving of output and computer time since the transformation is

$$V_j = \sum_k RC_{jk} V_k$$

$$\sigma = RC\,\sigma_o RC^T$$

with the results given numerically and plotted if a phase plot request existed in the original Option 0 data deck, see the following example.

```
Second order

 0
 1. ________
22. ________
17. ________
 .
 .
 .
24.     123416.
73.
 Track Vectors
 1  ________
22. ________
22. ________
22. ________
 4
 0
73.
```

Special input cards can be used with Option 4 on second order TRANSPORT to generate large numbers of points in multi-dimensional phase space and transform these points with the RC-matrix. The transformed points may then be plotted in various histograms and scatter plots. These special input cards for use with Option 4 are;

ADD	Next vectors will be added
CLEAR	End add option
ELLIPSE	Grid of vector generator will have elliptical boundary.
MATRIX	Initialize matrix to unit matrix
PRINT	Print vectors as they are generated
PUNCH	Punch matrix and vectors on tape 7
RANDOM, N	Specifies how many random variables are to be used.
14.....	First order matrix input
22.....	Vector generator
24.....	Plot

Generation of points in the multidimensional vector space is conventiently accomplished by use of the vector generator card. Its general format is

22. A1. A2. DA. B1. B2. DB. – ABCDER.
C1. C2. DC. D1. D2. DD. E1. E2. DE.

Where A, B, C, D and E are associated with the TRANSPORT coordinates X, XP, Y, YP, and dP/P according to the numeric value assigned to the tag –ABCDE. 1 corresponds to X, 2 to XP, 3 to Y, 4 to YP and 6 to dP/P, so that if A, B, C, D, and E are to be interpreted as Y, YP, X, XP and dP/P, then the tag –ABCDE would be –34126.

The values assigned to each variable is then taken on the regular interval

$$a_{J+1} = a_J + DA; \quad J = 1, \frac{A2-A1}{DA}, \quad a_1 = A1$$

R is the random flag. If R = 0 the flag is off and the values of the parameters are stepped on a regular grid. If R = 1, 2, . . . 9 the random flag is on. If the random flag is on, the number of values generated is the same as if the values were on the given grid, but the values are chosen randomly.

The number of values produced for the first variable A is NA. Then NA = (A2-A1)/DA+1 and the total number of vectors generated for a two-dimensional space is NA*NB. The maximum number of vectors allowed is 1024.

A two-dimensional vector generation requires only one data card. Therefore, to step over a grid of values in the X - XP plane, the generator card would have its eighth entry as -120.

22. A1. A2. DA. B1. B2. DB. -ABR.

Often one wishes only to randomize certain dimensions while stepping the others on a regular grid. This may be accomplished by the "RANDOM, N" entry, where N is the number of vector dimensions to be randomized. These must be the first dimension and the vector generating card, e.g.,

RANDOM 2
22 A1 A2 DA B1 B2 DB –36241
C1 C2 DC D1 D2 DD

Will cause Y and dP/P to be chosen randomly, while XP and YP will be taken on a regular grid.

The vectors so generated can be projected on various coordinates creating histograms or scatter plots. The plot card has the following format:

24 JK S1 S2 S3 S4 BIN X1 X2 XP1 XP2 Y1 Y2 YP1 YP2 DP1 DP2

Plots can be one or two dimensional as specified by the JK value. The value of J and K is related to the desired planes in the same way as the vectors are related, i.e.,

J, K= 1(X), 2(XP), 3(Y), 4(YP), 6(dP/P).

The scales of the plots can be specified by the 3rd through the 6th entry on the plot card. S1, S2, S3, and S4 are the specified scales of the plots. If the scales are zero, then the code will determine the scales so as to fit all the points on the plot. Histograms are produced if only J is entered. The maximum number of vectors that can be histogramed is 1024. To plot the X plane histogram enter 24. 1. For example: Two dimensional scatter-plots are specified by entry of both J and K, i.e., an X-Y plot is produced by entry of 24. 13. etc. Currently, the maximum number of vectors that can be scatter-plotted is 882. The 7th entry is not used in the 2-D plots. The number of bins in the histogram is entered as the 7th entry or the default value of 100 is taken. If non-equal entries are made for the 8, 9th 10, 11th 12, 13th 14, 15th and 16, 17th entries, then only vectors whose values in the given parameter lie between these limits will be plotted on the scatter plots or histograms.

The first four rows of the first order transformation matrix can be inputed by use of the 14. data cards. Four such cards are required, one for each row.

14.	R11	R12	R13	R14	R15	R16
14.	R21	R22	R23	R24	R25	R26
14.	R31	R32	R33	R34	R35	R36
14.	R41	R42	R43	R44	R45	R46

Such input will clear all second order terms.

Vectors may be accumulated so that plots will show previous vectors plus those added by subsequent vector generations. This is accomplished by the "ADD" card. To turn off the add option one enters a "CLEAR" card.

If one wants to plot the initial vectors, the RC transformation matrix must be set to a unit matrix so that the subsequent vector transformations will yield the initial vectors generated. This can be accomplished by the "MATRIX" card.

The vectors generated and transformed will not normally be printed as output. The printing can be initiated by entry of a "PRINT" card.

The transformed vectors can be written to tape 7 by entry of a "PUNCH" card. This will cause the following to be written to tape 7:

Date and case number	(1H1, 7A10, A9)
Title card	(1X, 7A10)
First order transfer matrix 6 cards in format	(7X6E12.4)
Number of vector cards, NV to follow	(1XI4)
NV cards giving the transformed N.X.XP. Y.YP.dP/P	(1XI4, 3X5E14.6)

EXAMPLE

```
SOLVE BEAMLINE SYSTEM
0                                   $ OPTION 0 DATA INPUT
.
.
5.01 1. 2. 4.                       $ VARIABLE
.
10 2 1 0 .001                       $ CONSTRAINT CARD, UPDATES RC MATRIX
73.                                 $ OPTION 0 CASE TERMINATOR
FIX SYSTEM,  CALC RC MATRIX         $ NEXT CASE TITLE CARD
2                                   $ OPTION 2 DATA INPUT
FIX                                 $ FIXES THE DATA
0                                   $ OPTION 0
73                                  $ TERMINATOR, CALCULATE RC-MATRIX
PLOT VECTORS                        $ TITLE CARD NEXT CASE
4                                   $ OPTION 4 DATA INPUT
22 OR5 2.5 0                        $ SET DP/P TO 2.5 PERCENT
22 0 1 .1 0 17 .2 -129.             $ GENERATE 946 RANDOM VECTORS
24 12                               $ SCATTER PLOT X-XP PHASE PLANE
24 1                                $ HISTOGRAM X-PLANE
0                                   $ END OPTION 4
73 73                               $ END JOB
```

The generation of the multidimensional vector space can be forced to occur inside a multidimensional elliptical boundary by use of the ELLIPSE option instead of the 22. vector generator. The input is

ELLIPSE, V1. V2. V3. V4. V5. N. -ABCDER.

where V1, V2, ... V5 will be the elliptical semiaxis associated with coordinates X, XP, Y, YP or dP/P according to the numeric value assigned to the tag -ABCDE (A, B, C, D, E = 1(X), 2(XP), 3(Y), 4(YP), 6(dP/P)). N is the number of vectors to be generated within this elliptical boundary. R is the random flag, with the vectors generated on a uniform grid if $R \equiv 0$ or chosen randomly if $R \neq 0$. Note that the ELLIPSE option necessarily operates a vector distribution whose centroid is centered on the pariaxial trajectory.

OPTION 5

Option 5 will produce a polygon calculation provided the appropriate cards have previously been inserted into the basic data deck. The required cards are the 13. 5. and either a 13. 6. or 13. 7. data card as previously described. As an example, consider solving a beam line, fixing the variables and constraints, adding a downstream spectrometer, and calculating the polygon. The data deck structure would be:

```
Basic data deck
0
1._________
13. 5.                    $ point of origin for polygon
.
.
5.01_________
5.01_________
.
.
.
10._________
73.
Fix system and add spectrometer
Fix
0
3.____
4.____
3.____
13.  6.                   $ end point of polygon calculation
73.                       $ end option 0 input
Calculate polygon
5
____
73.
```

Section 4 - Interactive Transports

Since publication of the user guide for LBL teletype and vista transport,[8] LBL-951 numerous changes have been made to the LBL-interactive transports, TRAN3 and TRAN4. Consequently, this section contains the guts of LBL-951 and supersedes that report.

Teletype Input Options

Table 5 gives a summary of the teletype input options to be used with teletype transport, TRAN4. Table 6 gives a summary of the teletype input options to be used with the vista transport, TRAN3. On the following pages each of these summarized options will be explained in detail and occur in alphabetic order. Those which may only be used with TRAN4 will be designated by TRAN4 parenthetically attached to the option, similarly those options which may only be used with TRAN3 will have TRAN3 parenthetically attached to the option in the writeup which follows. If during execution of either TRAN3 or TRAN4 a non-existent or illegal option is requested no harm is done as the code will simply say—no such option. All options which follow and which do not have parenthetical attachments may be used with both TRAN3 and TRAN4.

ABORT

This entry will terminate the job executing the control cards following the "EXIT" card.

ABORTJK. ABORT JK will cause the job to abort after execution of overlay J,K. The permissible entries are: ABORT10, ABORT11, ABORT12, ABORT13, ABORT14, ABORT15, ABORT20, ABORT21, ABORT22 and ABORT16, and ABORT17 for the vista versions.

ALINE. Same as described under Option 2, section 3.

ALTER. Same as described under Option 2, section 3.

BEAM (TRAN3) or B

During a vista run, the user may which to flip back and forth between his data displays and his beam line. This is accomplished by MDATA and BEAM entries on the teletype. If the beam line display is to be started fresh, removing any rays, matrices, or scale changes, this is accomplished by a BEAM option followed by a CANCL option.

CANCL (TRAN3) or C

When a request is made which can not be acted upon for some reason a error message may appear on the vista screen requesting you to hit "C" for cancellation of the request. No other entry will be accepted. Data input then resumes in normal fashion.

DLINE. Same as described under Option 2, section 3.

FIN

This option terminates the run. The control cards after a "FIN" control card will be executed, otherwise the job is done.

FIX. Same as described under Option 2, section 3.

FORCE(TRAN4)

Many checks are made on the data entered via the teletype to see that it is legitimate data. Occasionally one may wish to make an illegitimate entry for which no checks will be performed. This can be accomplished via the force entry giving the data array index and the new value of this element of the data array.

FORCE, I, X.

Use this option with extreme care.

GO or G

Entrance of GO causes execution of the data in the data array. No optimization will be performed. No teletype output will be generated when using this option with TRAN3 (vista). The output for TRAN4 will always start with the statement "Executing case number--" and end with the line "Length = --".

LABLE (TRAN4) or L

This option allows the user to enter the parameters that should appear in the table printed when the table option is selected. The table may consist of any combination of up to 19 of the following parameters:

LABLE	DEFAULT	MEANING
TYPE	"	prints type code and number of each data line
LC	"	accumulated length
xBEAM	"	horizontal beam projection
yBEAM	"	vertical beam projection
xCENT	-	horizontal beam centroid shift
yCENT	-	vertical beam central shift
xAPE	-	horizontal apertures
yAPE	-	vertical aperture
x1	-	horizontal ray 1
y1	-	vertical ray 1
x2	-	horizontal ray 2
y2	-	vertical ray 2
.	-	.
.	-	.
.	-	.
x6	-	horizontal ray 6
y6	-	vertical ray 6

If the LABLE option is not used, or used with no parameter list the default lables will be used in the table. A typical entry to give the accumulated length, horizontal and vertical beam and horizontal beam centroid shift and the vertical extent of vector 5 would be:

LABLE, LC, xBEAM, yBEAM, xCENT, Y5

All subsequent table request will then produce tables given these parameters in that order.

MATRX or MA

MATRX, LOC, RC2, 1234 (TRAN 3)
MATRX, LOC, LIST .... (TRAN 4)

A MATRX location is generated by the occurrence of an one of the following data entrys 13 1, 13 3, 13 4, 13 8, 13 24, 13 42, and 13 48. All matrices will be stored during execution of transport and may be printed on the teletype by use of the MATRX Option. Only the first 40 such locations will be saved for teletype and vista use. The parameters on the MATRX option give the location of the desired output and a list of which matrices are required. The list is any combination of

R, RC, R3, RC2, SI, VEC (or VEC, 1, 2, 5 etc.)

These matrices are stored at the location (NAME or I-COUNT) associated with the first of the series of I-O cards specifying off line MATRX output (13. X. type cards)

MATRX, IO14, RC, SI, VEC, 3, 5

Will print the RC and SI matrix on the teletype and vectors 3 and 5. If the location is multibly named, then one may specify the NAME, N for the nth occurrence of name, e.g., for the 3rd occurrence of IO14 the entry would be,

MATRX, I014, 3, R RC2

If the MATRX generating I-O request is embedded in a repeat loop (9. N.----9. 0.) the desired repeat number may be appended to LOC with 0(zero), no-entry or 1(one) all equivalent, so that if the RC matrix generated by IOX is desired in the second repeat the entry could

MATRX, IOX, 2, RC

If IOX is multi-named, and the 4th occurrence is the one nested in the repeat loop, the entry would be

MATRX, IOX, 4, 2, RC

The general scheme being

MATRX, NAME, MULT, NREP, LIST .....

If the list is not entered, the code will use the last entered list. Also, if LOC and LIST is not given, the code will use the last entered value for LOC and LIST. The allowed entries are all of the following.

MA, NAME, SI ...RC
MA
MA, NAME
ETC.

MDATA (TRAN3) or M

Often the data array is so large that the vista screen will not accommodate the entire array. The entry of MDATA flips between the "pages" of the data in a circular fashion, the first of the data following the last of the data. The data displayed gives the index counter, name, and data lines for the data array.

If simply a number is entered on the teletype, the data display will begin with the correct I-count nearest that number at the top of the page (Display).

NAME or NA

The name option allows the user to rename his data array with the standard name convention internally generated by the code. The names will be generated by the type of data element. The standard name scheme is described under NAME of Option 2, section 3.

NCASE

An entry of NCASE requests the input of a new data case. This case can come from off-line by reading tape 5, or from on-line teletype entry of an entire data set, in which case the teletype requests the entry of a title, option, and standard data. The user then enters the standard data, with or without names with no further requests from the teletype. When he is through entering his data he enters a 73. and normal teletype options then become effective.

If the data is read from tape 5 and an end of file is encountered, a error diagnostic will be printed and the data case can then be entered via the teletype. All input is in field free format.

The run number will be sequentially advanced unless a second entry is made, e.g., NCASE, yes. Then a request of entrance of the date, and case number will be made. The acceptable entries are:

NCASE
NCASE, yes
NCASE, X, N

Any case can be taken from the input file (Tapes 5) in any order. For example, say you want to execute the 5th data case and then return to the 2nd data case, enter,

NCASE, NO, 5
GO
NCASE, NO, 2

Tape 5 will be read until data Case 5 is encountered. To back up to Case 2, Tape 5 is rewound and Case 1 and 2 read leaving Case 2 in the data array.

OUTPT

The off-line output generated by transport may be turned on or off by entering

OUTPT, YES
OUTPT, NO

PDATA or PD

The data stored in the data array may be printed on the teletype via the PDATA option. If the print time will be longer than 2 minutes a warning will be issued and the user can then cancel the print command or accept it. The data printed will consist of the standard transport data lines preceded by the storage index, and data line name. A portion of the data array may be printed by entering the index or names of the section to be printed. The permissible entries are:

PDATA	Print entire data array'
PDATA, N	Print line with index N = 1, 2, -300
PDATA, NAME N	Print line of name NAME N
PDATA, N1, N2	Print all data between N1 and N2
PDATA, NAME 1, NAME 2	Print all data between NAME 1 and NAME 2

POLYG
POLYG, MATRX

The interactive polygon calculation requires a 13. 5. and 13. 6. data card in the data deck. Then a teletype entry of POLYG will cause execution of the data and a print out of the polygon vertices and area on the teletype. If the entry POLYG is replaced by POLYG, MATRIX the matrix between the 13. 5. and 13. 6. card will also be printed.

PRINT, LOC, LIST. (TRAN3)

The print option on the vista transport will print the various matrices and vectors specified on LIST on the teletype for future reference, where LIST is any combination of

R, RC, RC2, R3, SI, VEC, or VEC, N

N is a string of integers specifying which vectors are to be printed. If N is omitted, all vectors will be printed. If only vectors 1, 3, 4, and 6 are desired, N = 1, 3, 4, 6.

PULL

This option allows a user to "PULL" a group of elements out of any one of the four data array's (DATA, SAVE, SAVE 2, SAVE 3) into a buffer. Each subsequent ALINE or DLINE option specifies the location in the data array where the pulled data is to be placed. In this way a set of data elements may be conveniently placed at many locations of the data array. An entry other than ALINE or DLINE following the PULL option concludes the PULL option and subsequent ALINE's and DLINE's have their usual meanings. Example:

```
PULL, M, NAME1, NAME2
ALINE, N1, N2, N3,.....
DLINE, N1, N2, N3,.....
ALINE, N1
.
.
.
```

M is the array from which the data NAME1 to NAME2 is to be pulled

M=0	DATA array
M=1	SAVE1 array
M=2	SAVE2 array
M=3	SAVE3 array

NAME2 does not have to be entered if only one element is to be pulled from array M.

The parameter list for ALINE and/or DLINE are the names or indenx counts where the PULLED data is to be inserted.

RAY (TRAN 3) or R

After execution of transport any vectors tracked may be added by the ray option onto the beam line display. The first six vectors may all be added together or they may be added one or more at a time. The possible teletype entries are:

```
RAY
RAY, N1
RAY, N1, N2, N3....
```

The RAY option would display all vectors on the beam line. If a series of one to six numbers follow, then these are the vectors which would be added to the beam line display. Only the first six vectors in transports data array may be displayed on the vista screen.

RAYS, N, . . . , C

The entry of Rays will display all vectors on the Vista(TRAN 3) screen. If C ends the entry all Rays displayed will be removed. If a list of integers 1 to 6 are included these Rays will be displayed.

RECAL or RE

The data card and vectors saved via the SAVE option may be recalled via the RECAL option. The recaled data can come from one of three arrays and may or may not be swapped between the chosen array and the data array depending on the input parameters entered.

```
RECAL
RECAL, 1
RECAL, 2
RECAL, N, SWAP
```

Where N = 1 or 2, RECAL and RECAL,1 gives same results, namely recal of the data saved in the Save 1 array via a SAVE,1 entry. The swap entry exchanges the data between the data array and the SAVE N array.

RESPN (TRAN 4)

The response option allows the user to turn on or off the teletype response of "NEXT" signifying the waiting of next data or option input from the teletype. The allowed entries are:

RESPN, YES
RESPN, NO

REVERSE. Same as described under Option 2, section 3.

SAVE or SA

Three auxiliary data arrays may be used to store the data in the data array and vectors for subsequent retrieval. They are the SAVE (the same as SAVE 1) SAVE2 and the SAVE3 arrays. The following entries will store the data and vectors in current use into the designated save arrays.

SAVE,1
SAVE,2
SAVE,3

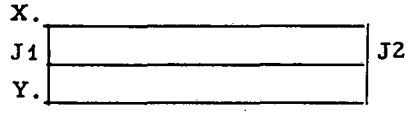
When no numeric is entered, the default is 1, i.e., the SAVE and SAVE,1 option give identical results. The data saved will only be changed by another save command. The data in the SAVE 1 array will be replaced by the reading of a next case (NCASE) command which automatically initiates a save command.

SCALE (TRAN 3) or SC

The beam line display obtained after a GO or SOLVE command may not show sufficient detail of a portion of the beam line. The SCALE option allows the user to insert the starting and ending point of the display and the horizontal and vertical scales. The data to be given via teletype is:

SCALE, J1, J2, X., Y.

Here J1, J2 are the data storage index or name at data line. This data will produce a plot



extending from J1 and J2 with maximum horizontal (X) scale or X and maximum vertical (Y) scale of Y. Any field may be void i.e., if only the horizontal scale is to be changed the data can be given as

Scale,,,X.

If only the longitudinal section is to be altered the data can be given as

Scale, J1, J2

Should the user wish to restore the original scale he may enter Scale with no other parameters. If the scale option has been selected by error, the cancel option may be used. Normally J1 and J2 will be the data array index counter such as displayed on the bottom of the beam line or along the left edge of the data display. Should the entered J1 and J2 not be correct the code will take the next larger correct value.

SEGMT (TRAN3), SEGMENTATION or SE

Many beam lines are a series of connected sections which can be considered to feed one another but other wise independent. Often the problem of "many variables and constraints" can be simplified by calculating each section or segment of the beam line independently, using the output of the preceding section or segment as input to the next section. This calculational procedure reduces the time and output since already solved sections are not recalculated as one optimizes each segment of his beam system individually.

The complete data set describing the entire beam line is read. After being displayed on the vista the user may segment the data by entering the section of the data which is to be calculated as the first segment. The first segment may start at any place on the beam, not necessarily at the beginning. The starting point and ending point being designated by the SEGMT option. Selection of the segmentation option via the teletype does three things, 1) saves the entire data array in the SAVE3 array, 2) processes all data cards and performs all beam calculations from the beginning of the original data up to the starting point of the segment; and 3) replaces the data displayed on the CRT screen and stored in the data array by the data de-limited between the starting and ending points selected.

The allowed inputs being of the form:

SEGMT, NAME 1, NAME 2
SEGMT, I1, I2
SEGMT, I1, NAME 2

All subsequent operations are upon this data now displayed and the calculations use as starting values of the σ, RC, RC2, R3 matrices and vectors the values calculated and saved for the beginning of this segment.

Example: Consider a beam line consisting of a quadrupole to produce a point to parallel beam and another quadrupole to produce a focus at a target. The original data set is shown in column 1.

Title Option	Title Option			Title Option	Title Option	
15		1.	1.	15	15	3.
15	15	5.10	5.	15	5	5.01
1.	15					3.
5.01		10.	-10.		1.	10.
10.	1.			1.	5.	
	5.01			5.	-10.	
3.	10.			-10		
5.01					3.	
	3.			3.	5.01	
3.	5.01			5.01	3.	
					10.	
10.	3.			3.		
73.	10.			10.		
	73.			73.	73.	

Column 2 shows a box around the data to be segmented by the teletype. The segmentation command is given and column 3 is produced after the constant, 15. data elements, are processed. Now a SOLVE command causes optimization of the quadrupole processing only the 1., 5.01, and 10. data element. After optimization the quadrupole can be fixed and the constraint negated by using the FIX option. This will fix all variable by zeroing out the vary codes and negate all 10. data cards as shown in column 4. This data can be stored in the saved data by using the save option. What ever data is displayed on the screen will replace the data in the appropriated section of the save array regardless of the number on lines inserted or deleted. The entire data array can now be recalled (RECAL) as shown in column 5. A box shows the data to be segmented as the next section as shown in column 6. Selection of the segment option causes calculation of the data from the 15. element up to the first drift space with the result of this calculation being saved and used as initial conditions for the segment de-limited by the box. The data as displayed is saved in the SAVE array and the section delimited by the box displayed on the screen and transferred to the data array as shown in column 7. The user is now ready to optimize this segment and proceeds in an analogous fashion for all subsequent segments of his beam line.

SNAPB (TRAN3) or SB

The beam line displayed on the vista screen will be copied to disc file SNAP via the SNAPB (Snap beam line) option. After the program is terminated, Snap may be copied to film inorder to generate a microfilm copy of the beam displays.

SNAPD (TRAN3) or SD

The data displayed on the screen of the vista will be copied to disc file SNAP via the SNAPD (Snap Data) option. The data can then be transferred to microfilm as described under SNAPB.

SOLVE or I

Entrance of the SOLVE option causes an optimization of any variables in the data array subject to the constraints in the data array. After completion of the optimization a automatic execution of the data (GO option) is issued. One of two optimization routines may be used,

standard optimization or variable metric optimization as specified by the data in the data array. Unless specifically requested, standard optimization is used. The output generated during optimization being:

```
EXECUTING CASENO  1-1
ACTUAL VALUE OF VARIABLES
(χ²) VARIABLE 1.   VARIABLE 2. ......
SOLVED (χ²)
```

If the data deck contains a 16. 29. -1. data line specifying variable metric optimization the output generated would be:

```
EXECUTING CASENO  1-2
STARTING VARIABLE METRIC OPTIMIZATION
     0-1 (χ²)   V1. V2. ....
     6-10 (χ²)  V1. V2. ....
     .
     .
     .
     .
SOLVED (χ²)
```

The output giving the iteration cycle, the number of times transport was executed to evaluate the chi-square, the current value of chi-square, and the value the variables currently have. This output line is printed every 5th cycle. If more or less output is desired the request can be made as a second parameter, SOLVE, N generating output line energy Nth cycle.

VARMIT INTERRUPT

During a varmit optimization, any entry to the teletype will stop the optimization. The value of the variables will be checked against the best values obtained and return of control made to the main program.

START

When one wishes to extend one case to another he may use the start option along with a special beam card in the next case. The use of this options allows the user to run decks which infact may use 400 to 600 data elements and would otherwise not fit into the data array in the usual way. After running the data with a GO option, enter START on the teletype. This will cause the R, RC, RC2, R3, SI, and vector matrices to be stored along with the accumulated length and beam momentum. In any subsequent data case in which the beam card is all zero (including the momentum) the values stored with the START entry will be used to initialize the various matrices and the accumulated length and beam momentum. In this way, the new data case is an extention of the previous case.

TABLE (TRAN4) or TA

A table may be printed after execution of transport giving the type codes, accumulated length, beam ellipsoid X, Y projections, centroid X, Y shifts and apertures that are encountered along the beam line by entering the TABLE request. If vectors are also being tracked, the X, Y positions of the first four vectors will also be printed. Since a complete table may take considerable time to print, facility is provided for entry of pairs of indexes or names bracketing the sections of beam line which should appear in the table. The possible entries might be:

TABLE	
TABLE, I1, I2	$I1 \leq I2$
TABLE, NAME 1, NAME 2	
TABLE, I1, I2, I3, I4, ...	$I1 \leq I2,\ I3 \leq I4, \ldots$
TABLE, I1, NAME 2, NAME 3, NAME 4, NAME 5, I6, ...	
etc.	

where I1, etc. are the data location index and the names are the names of the various data lines, as given by the pdata option. The first name of each pair must precede or equal the second name in the data structure, as the corresponding I of each pair is smaller than or equal to the second I.

TITLE or TI

This option allows the user to change the title of his data. The title appears at various places on the off-line output and so can be used for making appropriate comments for the various runs. The data entry is

TITLE, NEW TITLE etc.

TIME

An entry on the teletype of time will cause the printing of the number of computing units left for the job.

TLOC (TRAN4)

Often a user wishes to produce a table (TABLE option) at certain locations along his beam line many times during his teletype run. In order to relieve him of the necessity of entering the locations for which the table will be generated a default list may be defined via the TLOC option such that any entry of TABLE with no parameter list will use the default list as locations.

TLOC, NAME1, NAME2, ...

VECT

The vectors stored in the vector array may be added, altered, deleted or printed via the VECT option. If no vectors are in the data array they may be enterd via the ALINE option, not the VECT, ALINE option. Thereafter, all reference or changes of vectors is via the VECT option. Typical input lines might be:

VECT, ALINE, N, X, XP, Y, YP, S, DP, COMP.
VECT, ALTER, N, changes
VECT, ALTER, N, K, changes
VECT, DLINE, N1
VECT, DLINE, N1, N2
VECT, PRINT, N1, N2

In adding a vector, one needs only enter the numbers up to the last non-zero entry, the other parameters being automatically set to zero. The VECT, ALINE option will automatically increment the vector counter in the data array (number after the 22. element in the data array). To delete a vector one enters the vector number to be deleted. If more than one sequential vector is to be deleted, one enters the first and last vector number to be deleted.

To alter a vector already in data storage, one selects the VECT, ALTER option. The vector space X, X', Y, Y' $S, \delta P, \beta$ can be assigned a numeric equivalence 1, 2, 3, 4, 5, 6 and 7. Then to change the value of $S, \delta P$, which are the 5th and 6th positions on the Nth vector one enters

VECT, ALTER, N, 5, S, DP.

Up to 40 vectors can be transformed by transport. However, only the first six will be plotted on the beam line of the vista and only the first four will appear in the table of TRAN 4. All vectors will be printed at each location requesting the σ-matrix (13.-1.) on the teletype version.

Table 5. Teletype TRANSPORT (TRAN 4) operating instruction summary table.

```
ABORT
ABORT  JK - ABORT AT NED OF OVERLAY JK
AL     ALINE, NAME 1, NEW LINE.
A      ALTER, NAME, N, CHANGE
BL     BLINE, N1, N2, N3, N4 .......
D      DLINE, N1, N2
-      FIN
F      FIX, NAME 1, NAME 2
-      FORCE, N,X.
G      GO
L      LABLE, LABL, LAB2.....
           LABS=LABLES FOR TABLE OPTION
MA     MATRX, LOC, ENTRIES
       MATRX, LOC,N, ENTRIES
           ENTRIES=ANY COMBINATION OF SI, RC, RC2, R3, R, VEC
MV     MOVE, NAME 1, NAME 2, NEWLOC
            , NAME, NEWLOC
NA     NAME    ALL DATA
            , NAME, NEWNAME
-      NCASE
-      OUTPT
PD     PDATA, NAME 1, NAME 2
-      POLG
       POLYG,MATRX
-      PULL, M, NAME 1, NAME2
           M=0 DATA, M=1 SAVE, M=2 SAVE 2, M=3 SAVE 3
-      PUNCH
RE     RECAL
            , N
            , N, SWAP
-      RESPN, YES
            , NO
-      REVERSE, NAME 1, NAME 2
SA     SAVE, N
SE     SEGMT, NAME 1, NAME 2
I      SOLVE
-      START
TA     TABLE, N1, N2, N3, N4....
T      TITLE, NEWTITLE
TIME   TIME, PRINT THE AUS LEFT
-      TLOC, N1, N2, N3, N4....
V      VECT, ALTER, N,M, CHANGE
            , ALINE, N, NEWVECTOR.
            , DLINE, N1,N2
            , PRINT, N1,N2
```

Table 6. Vista TRANSPORT (TRAN 3) operating instruction summary table.

```
ABORT JK - ABORT AT END OF OVERLAY JK
A      ALTER, NAME, POSITION, CHANGE
AL     ALINE, NAME, NEWLINE .....
B      BEAM
C      CANCL
D      DLINE, NAME 1, NAME2
-      FIN
F      FIX
-      FORCE, N,X.
G      GO
MA     MATRX, LOC, MATRIX, PLANES.
       MATRIX=R OR RC OR RC2 OR R3, PLANES=1234 ETC.
M      MDATA
113    NUMERIC ENTRY WILL DISPLAY DATA STARTING WITH ENTRY.
MV     MOVE, NAME 1, NAME 2, NEWLOC
              NAME, NEWLOC
NA     NAME  ALL DATA
              NAME 1, NEWNAME
-      NCASE
-      OUTPT
PD     PDATA, NAME 1, NAME 2
-      PRINT, LOC, LIST
        LIST=ANY COMBINATION OF R RC RC2 R3 SI AND VEC.
-      PULL, M, NAME 1, NAME 2
        M=0 DATA, M=1 SAVE, M=2 SAVE 2, M=3 SAVE 3
-      PUNCH
R      RAYS            DISPLAY ALL
       RAYS, 1, 4, 5   DISPLAY 1, 4 AND 5
RE     RECAL OR RECAL, 2
       RECAL, 1, SWAP OR RECAL, 2, SWAP
        REVERSE, NAME 1, NAME 2
SA     SAVE OR SAVE, 2
SB     SNAPB
SC     SCALE, NAME 1, NAME 2, X, Y
       SCALE, C
SD     SNAPD
SE     SEGMT, NAME 1, NAME 2
-      START
T      TITLE, NEW TITLE
T      TIME, TIME PRINT THE AUS LEFT
I      SOLVE
V      VECT, ALTER, N, M, CHANGE
       VECT, ALINE, N, NEWVEC....
       VECT, DLINE, N1, N2
       VECT, PRINT, N1, N2
```

Table 7. TRAN 4 overlay structure.

```
FIELD LENGTH
1000 OCTAL
  0 ------------------------------------------------------------
  1 I                                                            I
  2 I                                                            I
  3 I                 OVERLAY(0,0)                               I
  4 I                       MAIN PROGRAM                         I
  5 I                       AND I-O BUFFERS                      I
  6 I                       LABLED COMMONS                       I
  7 I                                                            I
 10 I------------------------------------------------------------I
 11 I      BLANK COMMON  540 OCTAL                              I
 12 I--------------------------------------I                     I
 13 I                                      I                     I
 14 I                                      I                     I
 15 I        OVERLAY(1,0) GENDATA          I       BLANK         I
 16 I                                      I     COMMON          I
 17 I                                      I   7C40 OCTAL        I
 20 I--------------------------------------I                     I
 21 IOVERLAYIOVERLAYIOVERLAYIOVERLAYIOVERLAYI                     I
 22 I  NXT  IALTDATAIDATAPRTI  MISC ISEGDATAI                     I
 23 I (1,1) I (1,2) I (1,3) I (1,4) I (1,5) I                     I
 24 I-------I-------I-------I-------I-------I                     I
 25                                        I                     I
 26                                        I---------------------I
 27                                        I OVERLAY(2,C) TXEQ   I
 30                                        I---------------------I
 31                                        I       I       IOVERLAI
 32                                        I       I       I (2,3)I
 33                                        IOVERLAYIOVERLAYI DATA I
 34                                        I (2,1) I (2,2) I CHK  I
 35                                        I CUTBM ISCLVBM I
 36                                        I       I       I------I
 37                                        I       I       I
 40                                        I       I       I
 41                                        I       I       I
 42                                        I       I       I
 43                                        I       I       I
 44                                        I       I       I
 45                                        I       I       I
 46                                        I       I       I
 47                                        I       I       I
 50                                        ----------------
```

Section 5 - Running at LBL

AVAILABILITY OF BERKELEY TRANSPORT CODE

At present some computer time is made available by the Lawrence Berkeley Laboratory to federal agencies, institutions, and firms that have federal contracts or grants. For information about this and the LBL Computing Facility contact either

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LBL TRANSPORTS

In order to effectively conserve computer core size and calculation speed, we maintain five different versions of TRANSPORT at the Lawrence Berkeley Laboratory, two for batch processing and three for interactive calculations. These are as follow:

TRAN2	First order batch
TRAN22	Second order batch
TRAN4	First order teletype interactive
TRAN3	First order vista interactive
TRAN42	Second order teletype interactive

Control card examples and use of these TRANSPORTS will be given in this section.

LOADING AT LBL

A few words might be appropriate concerning the multiplicity of control cards used with transport here at LBL. Inorder to conserve data cell space all LGO files (Loader input files F, P, and R) have been run through UPTIGHT which compresses them into a single record. In order to recover them they must be un-uptight-ed as shown in several examples following. The files have also been run through LIBGEN so they may be used as library files to the link loader. The program replacement files for use with the R-file on the loader must be used for the interactive versions. All versions of the off-line TRANSPORT have the program files in the form of

```
PROGRAM TRANX(INPUT, OUTPUT, TAPES=INPUT, TAPE6=OUTPUT ..... )
```

All versions of the interactive TRANSPORT have their program files in the form of

PROGRAM TRANX(TAPE5, OUTPUT, TAPE7, TAPETTY, ...)

TAPE1=TAPETTY as the teletype file, TAPE5 as the input file TAPE6=output, and TAPE7 as a special punch file.

Setting Field Length

The interactive TRANSPORT will manipulate its own field length. During TTY-interaction the field length will be set to 24K octal words of memory where as during TRANSPORT execution the field length will automatically be uped to 52K octal. Should the messages printed on the teletype be bothersome, they may be suppressed by an entry of > N and turned back on again by entry of >Y.

Setting Output Line Limit

```
LINK, F=,R=, P=, L=, B=XECUTE.
XECUTE(NL=77777, INPUT, OUTPUT)
EXIT.
```

Where NL= gives the maximum number of lines that may be written to output.

Table 8A. TRANSPORT data cell subsets and file type.

SUBSET	LAST CHANGE	TYPE	OVERLAY FIELD LENGTH	NON-OVERLAY FIELD LENGTH	REFERENCE
T2LIB	3/15/74	ULP,F	-	120K	2038602
TRAN2	3/15/74	O	54K	-	2038602
T2RPL	3/15/74	ULR	-	-	2038602
-					
T3MAIN	3/15/74	O	52K	-	3033061
T3RPL	3/15/74	ULR	-	-	3033061
T3LIB	3/15/74	ULP	-	-	3033061
-					
T4MAIN	3/15/74	C	52K	-	4014868
T4RPL	3/15/74	ULR	-	-	4014868
T4LIB	3/15/74	ULP	-	-	4014868
-					
T22LIB	2/13/74	ULP,F	-	130K	2209046
TRAN22	2/13/74	C	70K	-	2209046
T22RPL	2/13/74	ULR	-	-	2209046
-					
TRAN42					
T42RPL		ULR	-	-	
TEXT		C	-	-	
UPTIGHT		C	-	-	

TYPE= TYPE OF RECORD ON DATA CELL

C=FILE TO BE COPYED DIRECTLY TO OUTPUT
F=F FILE FOR LINKX
L=LIBGEN-ED LGO FILE
O=OVERLAY LGO FILE
P=P FILE FOR LINKX
R=R FILE FOR LINKX
S=SOURCE FILE OR UPDTAE
U=UPTIGHTED LGO FILE

Table 8B. Link file substitution table for the various versions of TRANSPORT.

LINK	F=	R=	P=	P=	P=
(TRAN2)	T2LIB				
(TRAN2)	TRAN2	T2RPL	T2LIB		
(TRAN3)	T3MAIN	T3RPL	T3LIB	T4LIB	T2LIB
(TRAN4)	T22LIB	T4RPL	T4LIB	T2LIB	
(TRAN22)	T22LIB				
(TRAN22)	TRAN22	T22RPL	T22LIB		
(TRAN42)	TRAN42	T42RPL	T4LIB	T22LIB	

Control Card Examples, Off-Line

TRAN2

FOR 7600 AND 6600 NON-OVERLAY TRANSPORT

```
T2LIB,5,100,120000.999999,J.C.USER
LIBCOPY(TRANSPORT,X,UPTIGHT,T2LIB)
COPY(X/RB,1R,UPTIGHT)
UPTIGHT(X,LGO)
LINK,X.
EXIT.
DMPS.
-7-8-9-
```

FOR 7600 AND 6600 OVERLAY TRANSPORT FIRST ORDER

```
TRANS,5,100,55000.999999,J.Q.USER
LIBCOPY(TRANSPORT,X,UPTIGHT,TRAN2,T2LIB,T2RPL)
COPY(X/RB,1R,UPTIGHT)
UPTIGHT(X,LGO)
UPTIGHT(X,T2LIB)
UPTIGHT(X,T2RPL)
LINK,B=OQM,F=LGO,R=T2RPL,P=T2LIB,LO=0.
OQM.
EXIT.
DMPS.
COPY(MAPFILE/RB,OUTPUT)
-7-8-9-
```

TRAN22

NON-OVERLAY 2-ND ORDER TRANSPORT

```
T22LIB,5,100,130000.999999,J.C.USER
LIBCOPY(TRANSPORT,X,UPTIGHT,T22LIB)
COPY(X/RB,1R,UPTIGHT)
UPTIGHT(X,LGO)
LINK,X.
EXIT.
DMPS.
-7-8-9-
```

OVERLAYED TRAN22 FOR 7600 AND 6600

```
TRAN22,5,100,75000.999999,J.Q.USER
LIBCOPY(TRANSPORT,X,UPTIGHT,TRAN22,T22RPL,T22LIB)
COPY(X/RB,1R,UPTIGHT)
UPTIGHT(X,TRAN22)
UPTIGHT(X,T22RPL)
UPTIGHT(X,T22LIB)
```

RUNNING AT LBL
CONTROL CARD EXAMPLES, OFF-LINE

```
LINK,B=OQM,F=TRAN22,R=T22RPL,P=T22LIB.
OQM.
EXIT.
-7-8-9-
```

TRAN4

```
6600 INTERACTIVE TELETYPE TRANSPORT
     TRAN4,12,500,51000.999999,J.Q.USER
     *B
     LIBCOPY(TRANSPORT,X,UPTIGHT,T4MAIN,T4LIB,T4RPL,T2LIB)
     COPY(X/RB,1R,UPTIGHT)
     UPTIGHT(X,T4MAIN)
     UPTIGHT(X,T4LIB)
     UPTIGHT(X,T4RPL)
     UPTIGHT(X,T2LIB)
     TTY.
     COPY(INPUT,1R,TAPE5/RBR)
     LINK,F=T4MAIN,R=T4RPL,P=T4LIB,P=T2LIB,B=CQM,LO=0.
     OQM(TAPE5)
     EXIT.
     DMP.
     WBR.
     DMPS.
     FIN.
     REWIND(TAPE7)
     COPYSBF(TAPE7,OUTPUT)
     -7-8-9-
```

TRAN3

```
6600 INTERACTIVE VISTA TRANSPORT
     TRAN3,17,500,51000.999999,J.Q.USER
     *B
     DISPOSE,SNAP=TF,M=TV,R=[FLOOR 3].
     LIBCOPY(TRANSPORT,X,UPTIGHT,T3MAIN,T4RPL,T3LIB,T4LIB,T2LIB)
     LIBCOPY(TRANSPORT,X,T3RPL)
     COPY(X/RB,1R,UPTIGHT)
     UPTIGHT(X,TRAN3)
     UPTIGHT(X,T4RPL)
     UPTIGHT(X,T3LIB)
     UPTIGHT(X,T4LIB)
     UPTIGHT(X,T2LIB)
     UPTIGHT(X,T3RPL)
     COPY(INPUT,1R,TAPE5/RBR)
     REQUEST TAPE99,TV. VISTA 42
     TTY.
     LINK,B=OQM,F=TRAN3,R=T3RPL,R=T4RPL,P=T3LIB,P=T4LIB,P=T2LIB,LO=0.
     OQM(TAPE5)
```

RUNNING AT LBL
CONTROL CARD EXAMPLES, OFF-LINE

```
EXIT.
DMP.
WBR.
DMPS.
FIN.
COPY(SNAP/RB,FILM)
RETURN(TAPE99)
REWIND(TAPE7)
COPYSBF(TAPE7,CUTPUT)
-7-8-9-
```

TRAN42

```
6600 INTERACTIVE SECOND ORDER TELETYPE TRANSPORT
*8
LIBCOPY(TRANSPORT,X,UPTIGHT,TRAN42,T4LIB,T42RPL,T22LIB)
COPY(X/RB,1R,UPTIGHT)
UPTIGHT(X,LGO)
UPTIGHT(X,T4L)
UPTIGHT(X,T42R)
UPTIGHT(X,T22L)
COPY(INPUT,1R,TAPE5/RBR)
TTY.
LINK,P=T4L,R=T42R,P=T22L,B=OQ ,LO=0.
OQM.
EXIT.
DMP.
WBR.
DMPS.
FIN.
REWIND(TAPE7)
COPYSBF(TAPE7,OUTPUT)
-7-8-9-
```

Starting a Teletype or Vista Job

A teletype job may be submitted through a card reader or through the Berkeley Remote Facility SESEME. In either case, the control and data cards are identical; only the submittal device differs.

When submitting via a card reader, the user simply reads in his deck and connects his teletype to his job and waits for it to start execution.

When submitting via the SESEME, the user first connects his teletype to the SESEME, enters the editor, and types in his control and data cards as shown in Table 9. These entries may be saved via a STORE, X for future use and retrieved with a LOAD,X from the teletype, X should be a unique name. In any case, after entry of his data he submits his job by SC.

When the program begins execution it prints "PROGRAM EXECUTING--TYPE READY, STOP OR ABORT", the appropriate response by the user to start his program being READY. Table 10 shows the first set of exchanges between the computer and the user starting his teletype run. The arrows indicate user entries in response to the questions printed by the teletype.

After the first data deck has been read and is stored in the data array, the teletype will print "NEXT" indicating that it is ready for the next option to be entered.

Table 11 shows the results of entering PDATA or PD for print data. The data print lines give first the index counter, name of line, and then the data line as given by the user. An example of typical teletype output available to the user after executing his data with a GO is shown in Tables 12, 13, and 14. Each table begins with the teletype entry required to produce the output shown.

Table 9

```
>LØG!
LØGIN  CP-21  TTY-077  15.17.34.**BKY57C*B*08/20/74.
ENTER JØB CARD ØR ↑STØP
TRANS,12,500,51000.981172,A.C.PAUL
TRANS03 LØGGED IN.  SESAME 1.3 ENTERING ↑EDIT
ØK - ↑EDIT
1 TRAN4,12,500,51000.981172,A.C.PAUL!
2 *B!
3 FLØØR(3)!
4 LIBCØPY(TRANSPØRT,X,UPTIGHT,T4MAIN,T4RPL,T4LIB,T2LIB)!
5 CØPY(X/RB,1R,UPTIGHT)!
6 UPTIGHT   (X,T4MAIN)!
7 UPTIGHT(X,T4RPL)!
8 UPTIGHT(X,T4LIB)!
9 UPTIGHT(X,T2LIB)!
10 TTY.!
11 CØPY(INPUT,1R,TAPE5/RBR)!
12 LINK,B=ØØM,F=T4MAIN,R=T4RPL,P=T4LIB,P=T2LIB,LØ=0.!
13 ØØM(TAPE5)!
14 EXIT.!
15 FIN.!
16 REWIND(TAPE7)!
17 CØPYSBF(TAPE7,ØUTPUT)!
18 EØR!
19 TEST TRANSPØRT - 8-21-74!
20 0!
21 13 2!
22 22 ØR5 1!
23 1 .5 20 .5 20 0 0 .310!
24 3.4!
24 3 3.4!
25 5.01 .5 5 4!
26 5.01 .5 -5 4!
27 3 2!
28 13 1!
29 10 2 1 0 .001!
30 10 4 3 0 .001!
31 3 1!
32 24 0 !
33 73.!
34 EØR!
↑STORE,T4XMPL
↑SC.
```

Table 10

```
PRØGRAM EXECUTING -- TYPE READY, STØP ØR ABØRT

→ READY!
  TELETYPE INPUT ØPTIØNS ARE
  ABØRT  ALINE  ALTER  DLINE  FIN    FIX    FØRCE
  GØ     MATRX  MØVE   NAME   NCASE  ØUTPT  PDATA
  PØLYG  PUNCH  PULL   RECAL  REVER  RESPN  SAVE
  SEGMT  SØLVE  START  TITLE  TIME   VECT
  LABLE  TABLE  TLØC
  -----------
   DØ YØU WANT ØFF-LINE PRINT
→ YES!
   ENTER DATE
→ 8/20/74!
   ENTER CASE NUMBER
→ 1!
   IS DATA TØ BE ENTERED ØFF-LINE
→ YES!
  NØ.TAPE5=  1
  LIVERMØRE LØNG FRØNT END SYSTEM
       I1=132
  NEXT
```

Table 11

Teletype output obtained by the print data option PD.

```
PD!
YØU HAVE REQUESTED   3.93 MINETS ØF ØUTPUT SHØULD I PRØCEED
YES!
----
OLIVERMØRE LØNG FRØNT END SYSTEM
 0
   1-IØ1     13.0 2.0
  3-UNIT1   15  4 ØP5     1.00000
  7-UNIT2   15  1 IN      2.54000
 11-UNIT3   15  8 IN       .02540
 15-UNIT4   15  9 KG      1.00000
 19-UNIT5   15 11 MEV      .00100
 23-VEC1    22  3
             .5 0 .5 -0 -0 -0 -0
             0 20.0 0 20.0 -0 -0 -0
             0 0 0 0 0 1.0 -0
  25-BEAM1   1.0 .5 20.0 .5 20.0 0 0 38.74
  33-DA1     16.0 21.0 2.0
  36-DA2     16.0 4.0 5.0
  39-DA3     16.0 5.0 2.0
  42-BM1     4.0 10.0 22.5 .5
  46-L1      3.0 60.0
  48-Q1      5.0 10.0 1.0 4.0
  52-Q2      5.0 10.0 -.9 4.0
  56-L2      3.0 60.0
  58-L3      3.0 60.0

  60-Q3      5.0 10.0 -.88 4.0
  64-Q4      5.0 10.0 1.29 4.0
  68-L4      3.0 30.0
  70-L5      3.0 30.0
  72-BM2     4.0 10.0 22.5 0
  76-BM3     4.0 10.0 22.5 0
  80-L6      3.0 12.0
  82-Q5      5.01 10.0 .485 4.0
  86-Q6      5.01 10.0 -.509 4.0
  90-L7      3.0 72.0
  92-L8      3.0 73.0
  94-Q7      5.01 10.0 .9 4.0
  98-Q8      5.01 10.0 -1.05 4.0
 102-L9      3.0 36.0
 104-L10     3.0 36.0
 106-CØN1    10.0 2.0 1.0 0 .01
     FIT=   -0.
 111-CØN2    10.0 4.0 3.0 0 .01
     FIT=   -0.
 116-IØ2     13.0 4.0
 118-IØ3     13.0 1.0
 120-SLIT1   6.0 4.0 1.0 1.0
 124-L11     3.0 36.0

 126-PLØT1   24.0 0 4.5 4.5 -0 -0 -0
----
NEXT
```

Table 12

The beam matrix SI, vectors 1, 2, and 3, and the accumulated transformation matrix RC obtained on the teletype via the MATRIX option.

```
MATRX,I02,SI,VEC,RC!
 I02     125   579.000
 SI
      0.        .871 IN
      0.      11.615 MR      .152
      0.        .558 IN     0.     0.
      0.      36.902 MR     0.     0.      .874
      0.       3.320 CM     -.067  .976 0.     0.
      0.       0.     PC     0.     0.     0.     0.     0.
 VEC
 1(A)      .703   -5.355     .340  33.863  -2.136   0.      -0.
 2(B)      .515   10.307    -.442 -14.665   2.541   0.      -0.
 3(C)     1.136    3.312   0.       0.       .531   1.000  -0.
 RC
     1.40552      .02574    0.          0.          0.          1.13612
   -10.71017      .51535    0.          0.          0.          3.31176
     0.          0.          .67930    -.02212     0.          0.
     0.          0.        67.72626    -.73326     0.          0.
    -4.27298      .12707    0.          0.          1.00000      .53121
     0.          0.          0.          0.          0.          1.00000
NEXT
```

Table 13

Print out of the summary table on the teletype produced by the TABLE option, listing the values specified by the LABLE option.

```
LABLE LC XBEAM YBEAM XCENT X1 Y1!
NEXT
TABLE BM3 SLIT1!
------------
NAME     LC        XBEAM    YBEAM    XCENT    X1       Y1
------------
BM3      310.000   1.769    1.516    0.        .981    -.936
L6       322.000   1.818    1.577    0.       1.064   -1.034
Q5       332.000   1.647    1.824    0.       1.006   -1.246
Q6       342.000   1.465    2.035    0.        .945   -1.427
L7       414.000   1.591    1.784    0.       1.351   -1.479
L8       487.000   1.848    1.624    0.       1.763   -1.531
Q7       497.000   1.494    1.982    0.       1.440   -1.890
Q8       507.000   1.112    2.186    0.       1.088   -2.098
L9       543.000    .907     .884    0.        .896    -.879
L10      579.000    .871     .558    0.        .703     .340
SLIT1    579.000    .871     .558    0.        .703     .340

------------
NEXT
```

Table 14

Teletype output of the polygon calculation produced by the POLYG command. The basic data deck must have a 13. 5. and 13. 6. data entries to obtain this output.

```
PØLYG!
 EXECUTING CASENØ   1- 4
PØLYGØN AT 13.5.0 DELTAP=  -0.     PC          P=  38.740 MEV/C
 1    -.1848   48.9410 5.100 Q5          1.1654   29.0535 5.070 Q2
 2    -.2104   48.2019 5.082 Q4           .0059   33.5658 4.090 BM2
 3    -.9893   18.4322 5.112 Q7          -.0212   32.8656 4.090 BM2
 4   -1.0073   16.1530 6.138 SLIT1       -.9187    4.7005 5.116 Q8
 5     .1848  -48.9410 5.100 Q5         -1.1654  -29.0535 5.070 Q2
 6     .2104  -48.2019 5.082 Q4          -.0059  -33.5658 4.090 BM2
 7     .9893  -18.4322 5.112 Q7           .0212  -32.8656 4.094 BM3
 8    1.0073  -16.1530 6.138 SLIT1        .9187   -4.7005 5.116 Q8
APERTURES
HØRIZØNTAL PØLYGØN AREA=  94.0988 IN MR
   CENTER AT      .000 IN      -.000 MR

VERTICAL PØLYGØN AREA=  102.114 IN MR
   CENTER AT      .000 IN       .000 MR
NEXT
```

The best way to demonstrate the power and flexibility of TRANSPORT is to examine a number of examples of data and the results obtained. Before going on to the nine examples I will say a few words about standard output interpretation from TRANSPORT.

Standard TRANSPORT Output

The standard TRANSPORT output consists of print lines, on which left-most is a NEMONIC code, type code and parameter list for each data element processed by TRANSPORT during performance of the calculations, followed by the accumulated length, ICOUNT of the type code, and right-most on the print line occurring the data line name. Unless suppressed, the print of the beam ellipsoid, centroid, and vectors will occur after each element possessing a matrix, and will occur only where explicitly requested unless the 13. 40. option is used, in which case, the R and RC matrix will be printed after each element possessing a transformation matrix.

Since most of the output generated for each data element is just the data input, its interpretation should be obvious. Some extra output is generated by bending magnets, quadrupoles, and unit change. The angle of bend in degrees and the radius of curvature in units of drift length are printed for bending magnets, while the horizontal and vertical focal lengths of quadrupoles, -1/R(2, 1) and -1/R(4, 3), are printed after each quadrupole in units of drift length. A unit change generates a print line giving the value of the unit matrix which converts the user data into the internal set of units used by the computer.

At the end of each TRANSPORT calculation, a summary table will be printed giving the accumulated length, apertures, beam X, Y projections, centroid X, Y, and the first six vectors X, Y at the exit to each element of the beam line. This table forms the bases for the vista displays and beam line graph. The structure of the line is:

J TAG L APH APV H-BEAM V-BEAM H-CENT V-CENT HRAY1 VRAY1 NAME

The tag gives the type code with a unique decimal part appended giving the internal data storage index, I. e.g., 5.125 means a quadrupole (type code 5) stored in the 125-th location of the data array. L is the accumulated length. APH and APV are the half horizontal and vertical apertures. S(1, 1) and S(3, 3) are the horizontal and vertical phase space projections onto the coordinate axis and HR1, VR1, etc. are the X and Y values for the vectors. Only the first six vectors will be listed in the table. These projections include the necessary rotational transformations in order to project onto the global coordinate system irrespective of any beam rotations, type 20 elements in the beam line.

If betatron functions are to be calculated, a separate A-TABLE is printed, giving the value of the betatron functions along the beam line.

Any element of the RC, RC2, R3, S1, or correlation matrix may be included in the A-TABLE by use of the 16. KLM. IJ. data entry. This entry will store the desired value of the specified matrix into a vector location on the A-TABLE.

16. KLM. IJ.

K= RAY NUMBER
L= PLANE, =1 (X) =3 (Y)
M=STORAGE TYPE
M=1 RC(I, J)
M=2 RC2(I, J)
M=3 R3(I, J)
M=4 SI (I, J)
M=5 CORRELATION MATRIX, r (I, J)

During variable optimization, TRANSPORT prints out the RMS deviation to the constraints and the changes to the variables that it makes at each iteration. Following the table of changes, a table of the actual value of the variables is printed along with the RMS deviation obtained at these values. If TRANSPORT has failed to converge it will acknowledge this by printing "FAILED". When TRANSPORT fails, an additional line of output is generated under the heading "FOLLOWING OUTPUT RUN FOR VARIABLE PARAMETERS GIVING BEST FIT". This line gives the changes made to the variable in order to set them at the values giving the optimum (smallest) RMS deviation. The second run of transport is then made at these best values.

The variables are counted in the order in which they appear in the transport data. If several variables are tied together by coupled vary codes they are counted only once at the location of initial appearance, e.g., the following data sequence will produce the indicated convergence table.

Data Sequence

5.02	L.	B1.	A.	The quadrupoles coupled by the vary codes=
⋮				2, 3, 4, 5, 6, 7, 8 or 9 will be treated as a
5.01	L.	B2.	A.	single variable
⋮				
5.02	L.	B1.	A.	
⋮				
3.1	D1.			
⋮				
5.06	L.	B3.	A	
5.06	L	B3.	A.	
⋮				
3.4	D2			The 4 and 9 vary code couple the variables
⋮				so that a correction made to D2 will be
5.01	L.	B4.	A.	subtracted from D3 so as to maintain
⋮				D2+D3 = constant.
3.9	D3			
⋮				
5.01	L	B5	A.	

—

Corrections (RMS)	B1	B2	D1	B3	D2	B4	B5
Actual values of variables (RMS)	B1	B2	D1	B3	D2	B4	B5

When the variable matrix optimizer is turned on by a 16.29.-1. data card, the convergence output consists of a line for each direction chosen by the optimizer on the down hill gradient. This line gives the iteration step number, the number of calls to TRANSPORT to evaluate the RMS deviation at this point, the RMS deviation found, and the value of the variables.

A plot of the beam line will be made on the output paper following the beam line summary table if a 24.0. data card is encountered in the data deck. The graph will show all magnet apertures, the beam envelope trace, and the first six vectors in the horizontal and vertical planes. The graph scale may be set by the user or by default so as to contain all items to be plotted on a graph of two pages length. Table 15 shows the symbols used in making the graph.

Table 15

Symbol	Interpretation
B	Beam envelope projection.
1, 2, 3, 4, 5 or 6	Vector 1, 2, 3, 4, 5 or 6.
I	Center line of graph.
D	Drift space, type 3.
M	Bending magnet, type 4.
Q	Quadrupole magnet, type 5.
S	Slit. type 6.
E	Accelerator section, type 11
A	Auxiliary matrix, type 14.
X	Sextupole, type 18.
O	Solinoid, type 19
W	Separator, type 23.
*	Vectors or beam have exceeded scale limits.

The name of each element plotted will appear left-most on the plot. This name is the same as the data name used during input and/or alteration of the data.

A plot of the beam ellipsoid and particle vectors will be made on the output paper at the location of a 24. J. data card where J designates the beam phase plane, $11 \leq J \leq 65$. Figure 5-1 shows a typical horizontal phase plot as generated by TRANSPORT and its physical interpretation. Vector A was a null vector with 1% dispersion. Vectors C, D, E and F are of the central momentum and where started at points on the initial beam ellipsoid. Liouville's theorem and the linearity of the transformation guarantee that these vectors will lie on the transformed ellipsoid as can be seen in the figure. Vectors G, H, J and K where started at the same phase space location as vectors C, D, E and F but with 2% momentum deviation. Vectors G, H, J and K are dispersed by the bending magnets and can be thought of as representing a 2% beam ellipsoid as sketched in Fig. 5-1.

If two or more vectors lie at the same print position on the plot only the last vector at this position will show.

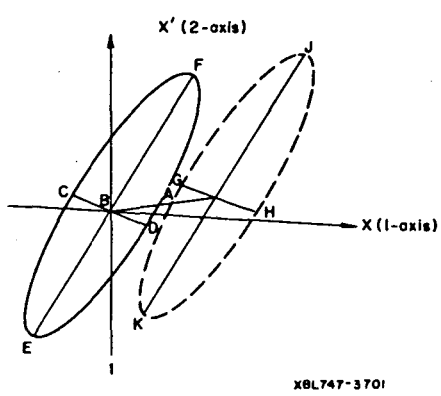


Fig. 5-1. Horizontal phase space for $\delta p/p = 0$ (vectors B, C, D, E, and F) and $\delta p/p \neq 0$ (vectors G, H, J, and K) showing approximated ellipse contours simulated by vector points.

EXAMPLE 1

As a first example, consider a quadrupole doublet lens required to produce a double focus some distance down stream for a 50 MeV proton beam. The data is shown in Fig. 5-2. The output from TRANSPORT is shown in Fig. 5-3 appropriate for the initial, unoptimized data. Figure 5-4 shows the beam plot for this data while Figs. 5-5 and 5-6 give the results for the data after optimization.

EXAMPLE 2

Next, consider the problem of calculating a muon channel for 130 MeV/c muons. In this system quadrupole Q1 collects pions from the production target and focuses them onto a slit, SLIT 1 at the center of a five quadrupole muon channel. The decay muons emerge from the channel, pass through bending magnet BM3-BM4 and are focused by a quadrupole doublet onto the target at SLIT 2.

In analyzing the system, the first section from the production target to the intermediate focus at SLIT 1 is run and optimized, as shown in Figs. 5-7, 5-8, and 5-9. The polygen calculation and the resulting channel acceptance are shown in Fig. 5-10. Next, the data is altered by Option 2 and the rest of the system added as shown in the data of Fig.5-11. The beam line graph for the entire line is shown in Fig. 5-12.

A radial focus occurs inside the last doublet where a momentum resolution of about 0.5% is obtained. Note that the vectors shown in Fig. 5-12 are transformed for a momentum 1% higher than the beam momentum shown enclosed by the "B' s" of the figure. Vector 2 is the 1% momentum deviation beam centroid and it crosses the pariaxial beam at SLIT 2. Also, note that the exact location of the vertical waist can be seen by the minimum projections of the vectors inside drift space L13. This occurs because the vectors were originally chosen to lie on the initial beam ellipse contour at several different phases of vertical oscillation.

The radial (horizontal) phase space acceptance of the total system for various momenta is shown in Fig. 5-13, and is a tracing from the plot produced by TRANSPORT, the areal overlap of this acceptance with the pion production target yields the momentum spectrum of the beam line, shown in Fig. 5-14.

EXAMPLE 3

This example demonstrates the use of TRANSPORT in following non-linear phase motion around the Escar ring lattice for 99 revolutions in second order. The time required for this calculation was 18 seconds on a CDC 7600 computer. The basic data deck (Option 0), Fig. 5-15 was set up so that the transformation matrix for a quadrant of the storage ring was stored as matrix 1, 25 element QUART. This matrix was multiplied by itself three times to generate the full Escar transformation matrix 2, 25 element FULLT. The data deck includes 16 data cards specifying that vector 2 in the A-table will contain the $\sqrt{\sigma(1,1)}$, $\sqrt{\sigma(2,2)}$ terms and vector 3 in the A-table will contain the x-xp position of vector 1. The quarter turn result is shown in Fig. 5-16.

To demonstrate resonance excitation of the lattice, case 2 calculates the full turn matrix plus or small sextupole exciter and stores this as matrix 4 (25 element) Escar. Case 3 then runs this Escar matrix for 99 revolutions, phase plotting vector 2 (x-xp of beam) Fig. 5-17 and vector 3 (x-xp for vector 1), Fig. 5-18.

EXAMPLE 4

This example shows the use of TRANSPORT in evaluating a K^- beam in the presence of a π^- contanimant. The beam layout is shown in Fig. 5-19 and the data in Fig. 5-20. The beam consists of quadrupole Q1 which is strongly horizontally focusing and determines the horizontal acceptance along with momentum slit. Bending magnet BM1 provides dispersion, vertical focusing, and 47.4 degree angular deflection to the beam. Quadrupoles Q2 and Q3 focus the beam on the momentum and mass slits at the far end of the particle separator. The beam passing through the slit system is made approximately parallel by Q4 and Q5 and passes through BM2 and quadrupole Q6 to the target at the end of the beam line.

Figure 5-21 shows the first and second order transformation matrix at end of the system. In order to better be able to estimate the significance of various second order aberrations the T*SIGMA matrix was generated by the 13. 42. data entry. The large elements of this matrix are the significant aberrations to the beam for this system at that location.

Figures 5-22, 5-23, and 5-25 show the envelope, vector and aperture plots generated by the 24. data card for three different runs of the beam line. The first run is to first order only with no momentum spread. The particle separator deflects vectors 2, 3, 4, 5 and 6 which simulates the first order π beam. Vector 1 shows the effects of a 1% momentum deviation.

Figure 5-23 is the beam plot through second order with $\delta p/p = 0$. The vectors are calculated through first order only. The increase in vertical beam size at the mass slits is due to the geometric aberrations introduced by the Bending magnet BM1. The π beam should be thought of undergoing a similar increase in size. Finally, Fig. 5-24 shows the actual beam condition with $\delta p/p = 2\%$. The further increase in the vertical beam size at the mass slit is brought about by the addition of the quadrupole chromatic aberrations to the beam. An analogous increase in the π beam should be obtained.

EXAMPLE 5

In this example we will show the use of TRANSPORT in calculating a beam line with many differing planes of projection. This beam is the delay line injection system for ASTRON. The electron Linac injector produces a space charge limited relativistic beam of 6 MeV electrons in a pulse of about 400 nsec. The ASTRON acceptance time is around 200 nsec, so it was desired to store the first 200 nsec of the Linac pulse by transferring it along a trombone delay line of some 1700 inches of solenoid magnets and inject simultaneously the two halves of the Linac pulse into ASTRON. The delay line system is shown in Fig. 5-25 and the TRANSPORT data for this system is shown in Fig. 5-26. The Kicker magnet deflects the beam 7 degrees into the delay line. Q1 and SOL1 were adjusted to match the beam to the non-deflected line, while SOL2, SOL3, SOL4, SOL5, and SOL6 were adjusted to match the beam to the long solenoids, i.e., to make the radial and vertical eigen ellipse the same in the two planes. Quadrupoles Q2, Q3, Q4, and Q5, Q6, Q7 were adjusted to make each of the 180 degree deflection systems nondispersive. SOL7 is used to twist the dispersion plane and SOL8 is used to match into ASTRON. Figures 5-27 and 5-28 show the horizontal and vertical phase space for several momenta and Fig. 5-29 shows the beam profile along the delay line.

EXAMPLE 6

The effects of magnet positional misalignments must be investigated in order to specify magnet position tolerances or to determine if a given beam line is unusually sensitive to slight locational perturbations. Example 6 shows a vertically separated pion beam where the positional accuracy of the vertical quadrupole Q1, preceding the particle separator and quadrupole doublet Q3-Q4 following the separator was investigated. The data is shown in Fig. 5-30 producing the beam line graph of Fig. 5-31. The vertical phase space at the location of the separator slit for several different misalignments of Q1, and Q3-Q4 are traced from the TRANSPORT plots onto Fig. 5-32.

EXAMPLE 7

Option 3 is very useful in finding solutions to problems which are sensitive to starting conditions. Consider finding the set of solutions for waist to waist transformation produced by a quadrupole triplet. For a given polarity of the symmetric triplet four solutions should exist with different horizontal and vertical magnifications. Figure 5-33 shows the data required to generate the ten optimal solutions found in Table 16. These 10 starting values were then solved for waist to waist transformations, the results given in Table 17. Figures 5-34 and 5-35 show the waist-waist graph and phase space ellipse of these several runs at different magnification.

Table 16

NUMBER	CHI	VARIABLE 1	VARIABLE 2	VARIABLE 0	VARIABLE 0	CONSTRAINED VALUES	
1	1.046E+04	5.000000	-4.000000	0.000000	0.000000	5.603E+00	1.479E+02
2	2.206E+04	6.000000	-4.000000	0.000000	0.000000	-1.969E+01	3.114E+02
3	3.917E+04	7.000000	-4.000000	0.000000	0.000000	-1.653E+01	5.537E+02
4	6.311E+04	8.000000	-4.000000	0.000000	0.000000	3.190E+00	8.925E+02
5	9.534E+04	9.000000	-4.000000	0.000000	0.000000	3.007E+01	1.348E+03
6	1.374E+05	10.000000	-4.000000	0.000000	0.000000	5.697E+01	1.943E+03

---------- BEAM LINE CALCULATION TIME= .092 SECONDS

NUMBER	CHI	VARIABLE 1	VARIABLE 2	VARIABLE 0	VARIABLE 0	CONSTRAINED VALUES	
7	8.394E+03	5.000000	-6.000000	0.000000	0.000000	1.176E+02	-1.614E+01
8	1.933E+03	6.000000	-6.000000	0.000000	0.000000	2.551E+01	-9.830E+00
9	2.521E+03	7.000000	-6.000000	0.000000	0.000000	-1.511E+01	3.230E+01
10	8.703E+03	8.000000	-6.000000	0.000000	0.000000	-2.133E+01	1.212E+02
11	1.936E+04	9.000000	-6.000000	0.000000	0.000000	-7.053E+00	2.694E+02
12	3.474E+04	10.000000	-6.000000	0.000000	0.000000	1.676E+01	4.910E+02

---------- BEAM LINE CALCULATION TIME= .074 SECONDS

NUMBER	CHI	VARIABLE 1	VARIABLE 2	VARIABLE 0	VARIABLE 0	CONSTRAINED VALUES	
13	2.717E+04	5.000000	-8.000000	0.000000	0.000000	3.409E+02	1.772E+02
14	1.320E+04	6.000000	-8.000000	0.000000	0.000000	1.495E+02	1.117E+02
15	4.739E+03	7.000000	-8.000000	0.000000	0.000000	3.998E+01	5.378E+01
16	1.026E+03	8.000000	-8.000000	0.000000	0.000000	-1.111E+01	9.327E+00
17	1.949E+03	9.000000	-8.000000	0.000000	0.000000	-2.330E+01	-1.472E+01
18	1.139E+03	10.000000	-8.000000	0.000000	0.000000	-1.233E+01	-1.037E+01

---------- BEAM LINE CALCULATION TIME= .074 SECONDS

NUMBER	CHI	VARIABLE 1	VARIABLE 2	VARIABLE 0	VARIABLE 0	CONSTRAINED VALUES	
19	6.716E+04	5.000000	-10.000000	0.000000	0.000000	7.036E+02	6.380E+02
20	4.811E+04	6.000000	-10.000000	0.000000	0.000000	3.736E+02	5.686E+02
21	3.660E+04	7.000000	-10.000000	0.000000	0.000000	1.647E+02	4.907E+02
22	2.893E+04	8.000000	-10.000000	0.000000	0.000000	4.548E+01	4.066E+02
23	2.259E+04	9.000000	-10.000000	0.000000	0.000000	-1.041E+01	3.193E+02
24	1.654E+04	10.000000	-10.000000	0.000000	0.000000	-2.467E+01	2.326E+02

---------- BEAM LINE CALCULATION TIME= .074 SECONDS

NUMBER	CHI	VARIABLE 1	VARIABLE 2	VARIABLE 0	VARIABLE 0	CONSTRAINED VALUES

TEN BEST (OPTIMUM) STARTING CONDITIONS FOUND

16	1.026E+03	8.000000	-8.000000	0.000000	0.000000
18	1.139E+03	10.000000	-8.000000	0.000000	0.000000
8	1.933E+03	6.000000	-6.000000	0.000000	0.000000
17	1.949E+03	9.000000	-8.000000	0.000000	0.000000
9	2.521E+03	7.000000	-6.000000	0.000000	0.000000
15	4.739E+03	7.000000	-8.000000	0.000000	0.000000
7	8.394E+03	5.000000	-6.000000	0.000000	0.000000
10	8.703E+03	8.000000	-6.000000	0.000000	0.000000
1	1.046E+04	5.000000	-4.000000	0.000000	0.000000
14	1.320E+04	6.000000	-8.000000	0.000000	0.000000

Table 17. Results from iteration of the ten optimal starting values generated by Option 3 for waist to waist transformations. Note the multiplicity of solutions representing different magnifications of the beam.

Optimization run	Initial fields Q1	Initial fields Q2	Final fields Q1	Final fields Q2	Horizontal beam size	Vertical beam size
1	8	-8	7.486	7.649	8.23	.88
2	10	-8	10.677	-8.138	.92	6.23
3	6	-6	6.582	-6.133	7.98	6.42
4	9	-8	19.26	-11.67	3.28	.871
5	7	-6	6.562	6.133	---	---
6	7	-8	7.488	-7.649	---	---
7	5	-6	-19.264	11.673	.871	3.28
8	8	-6	11.285	-9.194	.928	.876
9	5	-4	---	---	---	---
10	6	-8	---	---	---	---

EXAMPLE 8

This example demonstrates the use of the 25. element to input an entire second order transformation matrix and the use of Option 4 in calculating scatter plots and histograms. The basic data for the low energy pion channel (LEP) is given in Fig. 5-36. The data lines GAP (16.5, 7.62) to the second drift D2 (3., 0.55) give a nondispersive bending system with numerous second order corrections. The beam graph for this data is shown in Fig. 5-37. Figure 5-38 gives the same beam data with the lines GAP to D2 specifying the bending magnet system replaced by its first and second order transformation matrix. This replacement only occupies 4 spaces in the data array as shown in Fig. 5-39. Figure 5-40 shows the data for Option 4 which may operate on this beam system producing the representative plots shown in Figs. 5-41, 5-42, and 5-43.

EXAMPLE 9

When beam lines are encountered that are too long to run within the confines of 300 data points imposed by TRANSPORT, the LBL version allows a continuation of the beam, vectors, and matrices by use of Option 1. In order to continue the beam line the data deck should contain a beam tilt (type 12) and axis shift (type 7) card after the beam card. To demonstrate the use of beam continuation, consider the data shown in Fig. 5-44. This produces the beam line data and graph of Figs. 5-45 and 5-46 for the data LINK1 to END1.

To continue the line, Option 1 is used with the data shown in Fig. 5-47. The -1 beam card sets a KONTINU flag which prevents initialization of assundry parameters, sets the accumulated length to that of the previous case, and initializes the RC2 and R3 matrices to the values stored by the previous case in the RMATSV 14 and 15 array (this precludes the use of a 25. 14. or 25. 15. data entry in the data decks to be continued). The data for the beam card, tilt card, vector cards and axis shift is then initialized to the values at the end of the previous case. Option 2 is then used to delete the data describing the first part of the system (LINK1 to END1) and Option 0 is used to enter the next section (LINK2 to END2) and perform standard TRANSPORT calculations. The beam line data and graph produced by this data is shown in Figs. 5-48 and 5-49. Similarly, the data for LINK3 to END3.

```
6/18/74
1.
EXAMPLE 1  SIMPLE OPTIMIZATION OF QUADRUPOLE DOUBLET LENSE
0
13 2
16 29 -1 $ VARMIT OPTIMIZER
1  .3  35  .5  17  0  0  .310 $  50 MEV PROTONS
3 1.25
5.01 .5 5 10
3 .25
5.01 .5 -5 10
3 1.05
3 1.05
10 -1 2 0 .001 FH
10 -3 4 0 .001 FV
13 1
13 4
24
73
CHANGE FOCUS TO WAIST
2
A FH 2 2 1 0 .01
A FV 2 4 3 0 .01

SENTINEL
SENTINEL
```

Fig. 5-2. Data input to TRANSPORT for optimizing a simple quadrupole doublet for a focus condition.

```
DATE=6/18/74                                                                                                  CASE NUMBER  1-  0-F

EXAMPLE 1  SIMPLE OPTIMIZATION OF QUADRUPOLE DOUBLET LENSE
     1(Q1    )   13.000000    2.000000
     3(DA1   )   16.000000   29.000000   -1.000000
     6(BEAM1 )    1.000000     .300000   35.000000     .500000   17.000000    0.000000    0.000000     .310000
    14(L1    )    3.000000    1.250000
    16(Q1    )    5.010000     .500000    5.000000   10.000000
    20(L2    )    3.000000     .250000
    22(Q2    )    5.010000     .500000   -5.000000   10.000000
    26(L3    )    3.000000    1.050000
    28(L4    )    3.000000    1.050000
    30(FH    )   10.000000   -1.000000    2.000000    0.000000     .001000
    35(FV    )   10.000000   -3.000000    4.000000    0.000000     .001000
    40(Q2    )   13.000000    1.000000
    42(Q3    )   13.000000    4.000000
    44(PLOT1 )   24.000000   -0.000000   -0.000000   -0.000000   -0.000000   -0.000000   -0.000000

PAR  16.0   ( 29.0)        -1.00000
BEAM  1.000000     .31000 GEV/C                                          A-TABLE NO.= 1     LENGTH=    0.000 M    BEAM1 -  6
DRIFT 3.0    1.250 M                                                     A-TABLE NO.= 2     LENGTH=    1.250 M    L1    - 14
QUAD  5.01    .500 M     5.0000 KG  10.00 CM   (    .51 M  )            A-TABLE NO.= 3     LENGTH=    1.750 M    Q1    - 16
DRIFT 3.0     .250 M                                                     A-TABLE NO.= 4     LENGTH=    2.000 M    L2    - 20
QUAD  5.01    .500 M    -5.0000 KG  10.00 CM   (   -.34 M  )            A-TABLE NO.= 5     LENGTH=    2.500 M    Q2    - 22
DRIFT 3.0    1.050 M                                                     A-TABLE NO.= 6     LENGTH=    3.550 M    L3    - 26
DRIFT 3.0    1.050 M                                                     A-TABLE NO.= 7     LENGTH=    4.600 M    L4    - 28
FIT  10.0    -1  2   0.000000/  .001000
                     -.448562
FIT  10.0    -3  4   0.000000/  .001000
                     -.748489
                                                                  0.000  15.897 CM                LENGTH=    4.600 M
                                                                  0.000  68.506 MR    1.000
                                                                  0.000  12.949 CM    0.000 0.000
                                                                  0.000  94.413 MR    0.000 0.000 1.000
                                                                  0.000   0.000 CM    0.000 0.000 0.000 0.000
                                                                  0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
TRANSFORM 1

       -8.3310E+00 -4.4856E-01  0.          0.          0.          0.
       -3.3725E+01 -1.9359E+00  0.          0.          0.          0.
        0.          0.         -4.8024E+00 -7.4849E-01  0.          0.
        0.          0.         -3.3725E+01 -5.4644E+00  0.          0.
        0.          0.          0.          0.          1.0000E+00  0.
        0.          0.          0.          0.          0.          1.0000E+00
PLOTS 24.0          -0   -0.0000 CM    -0.0000 CM    -0.0000 M     -0.0000   -0.0000
LENGTH   4.600M

J  TYPE.III    L     APH        APV        H-BEAM     V-BEAM     H-CENT     V-CENT     HRAY1      VRAY1
 1  1.006    0.0300                        .3000      .5000      0.         0.         0.         0.          1  1.006-BEAM1
 2  3.014    1.2500                       4.385      2.183      0.         0.         0.         0.          2  3.014-L1
 3  5.016    1.7500   10.00      10.00    3.407      4.651      0.         0.         0.         0.          3  5.016-Q1
 4  3.020    2.0000                       1.659      6.949      0.         0.         0.         0.          4  3.020-L2
 5  5.022    2.5000   10.00      10.00    1.518      6.879      0.         0.         0.         0.          5  5.022-Q2
 6  3.026    3.5500                       8.705      3.037      0.         0.         0.         0.          6  3.026-L3
 7  3.028    4.6000                       15.90      12.95      0.         0.         0.         0.          7  3.028-L4
```

Fig. 5-3. Transport output generated before quadrupole optimization.

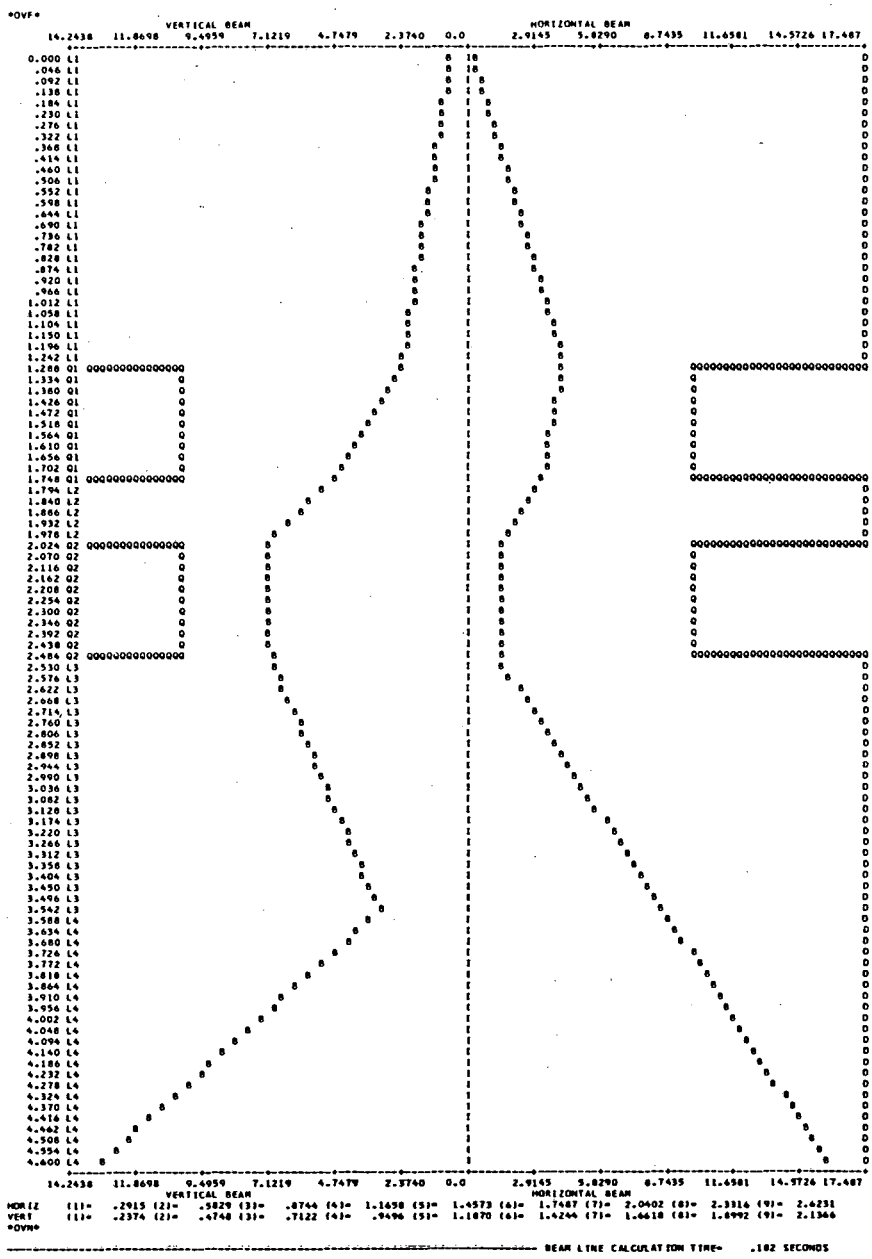


Fig. 5-4. Beam line graph for unoptimized doublet beam line.

```
DATE=6/18/74                                                                                                                    CASE NUMBER   1-  0-C

EXAMPLE 1  SIMPLE OPTIMIZATION OF QUADRUPOLE DOUBLET LENSE
   (FIT,      4.106E-01)
  .004
 -.397   .003

    1(IO1    )   13.000000    2.000000
    3(DA1    )   16.000000   29.000000   -1.000000
    6(BEAM1  )    1.000000     .300000   35.000000     .500000   17.000000    0.000000    0.000000     .310000
   14(L1     )    3.000000    1.250000
   16(Q1     )    5.010000     .500000    3.521773   10.000000
   20(L2     )    3.000000     .250000
   22(Q2     )    5.010000     .500000   -3.068315   10.000000
   26(L3     )    3.000000    1.050000
   28(L4     )    3.000000    1.050000
   30(FH     )   10.000000   -1.000000    2.000000    0.000000     .001000
   35(FV     )   10.000000   -3.000000    4.000000    0.000000     .001000
   40(IO2    )   13.000000    1.000000
   42(IO3    )   13.000000    4.000000
   44(PLOT1  )   24.000000   -0.000000   -0.000000   -0.000000   -0.000000   -0.000000   -0.000000

PAR  16.0   ( 29.0)        -1.00000
BEAM  1.000000     .31000 GEV/C                                                    A-TABLE NO.= 1     LENGTH=    0.000 M    BEAM1 -  6
DRIFT 3.0    1.250 M                                                               A-TABLE NO.= 2     LENGTH=    1.250 M    L1    - 14
QUAD  5.01    .500 M     3.5218 KG  10.00 CM   (    .68 M  )                      A-TABLE NO.= 3     LENGTH=    1.750 M    Q1    - 16
DRIFT 3.0     .250 M                                                               A-TABLE NO.= 4     LENGTH=    2.000 M    L2    - 20
QUAD  5.01    .500 M    -3.0683 KG  10.00 CM   (   -.60 M  )                      A-TABLE NO.= 5     LENGTH=    2.500 M    Q2    - 22
DRIFT 3.0    1.050 M                                                               A-TABLE NO.= 6     LENGTH=    3.550 M    L3    - 26
DRIFT 3.0    1.050 M                                                               A-TABLE NO.= 7     LENGTH=    4.600 M    L4    - 28
FIT  10.0    -1  2   0.000000/  .001000
                     -.000579
FIT  10.0    -3  4   0.000000/  .001000
                      .000038
                                                                    0.000   1.194 CM                LENGTH=    4.600 M
                                                                    0.000  10.174 MR      .503
                                                                    0.000    .268 CM    0.000 0.000
                                                                    0.000  32.307 MR    0.000 0.000   .194
                                                                    0.000   0.000 CM    0.000 0.000 0.000 0.000
                                                                    0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
TRANSFORM 1

      -3.9808E+00 -5.7935E-04  0.          0.          0.          0.
      -1.6569E+01 -2.5362E-01  0.          0.          0.          0.
       0.          0.         -5.3639E-01  3.8465E-05  0.          0.
       0.          0.         -1.2690E+01 -1.8634E+00  0.          0.
       0.          0.          0.          0.          1.0000E+00  0.
       0.          0.          0.          0.          0.          1.0000E+00
PLOTS 24.0         -0   -0.0000 CM    -0.0000 CM    -0.0000 M     -0.0000   -0.0000
LENGTH   4.600M

J  TYPE.III    L     APH        APV        H-BEAM     V-BEAM     H-CENT     V-CENT     HRAY1      VRAY1
 1  1.006    0.0000                        .3000      .5000      0.         0.         0.         0.          1  1.006-BEAM1
 2  3.014    1.2500                       4.385      2.183      0.         0.         0.         0.          2  3.014-L1
 3  5.016    1.7500   10.00      10.00    4.157      4.136      0.         0.         0.         0.          3  5.016-Q1
 4  3.020    2.0000                       3.073      5.811      0.         0.         0.         0.          4  3.020-L2
 5  5.022    2.5000   10.00      10.00    1.850      6.738      0.         0.         0.         0.          5  5.022-Q2
 6  3.026    3.5500                       1.133      3.351      0.         0.         0.         0.          6  3.026-L3
 7  3.028    4.6000                       1.194      .2682      0.         0.         0.         0.          7  3.028-L4
```

Fig. 5-5. Transport output generated after quadrupole optimization.

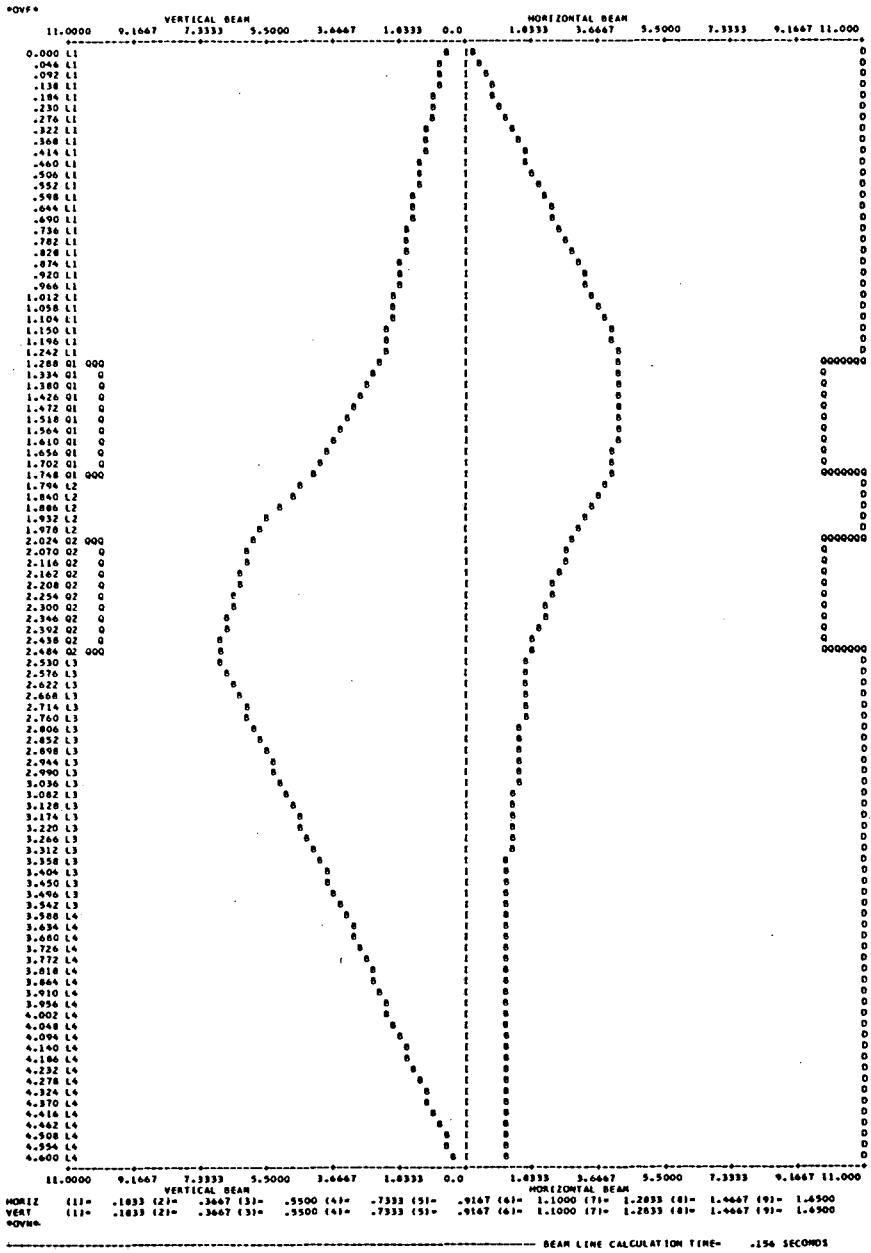


Fig. 5-6. Beam line graph for optimized doublet beam line.

```
6/18/74
1.
 130 MEV/C PION CHANNEL
0
15 6 0 0
15 1 M  100
15 2 RAD 1000
15 5  M 100
15 8 M 1
15 9 T 10
15 11 GEV 1.
22 OR6
22 OR5 1
22 .02 0 .005 0 0 1
22 0 .03 0 .03 0 1
22 -.02 0 -.005 0 0 1
22 0 -.03 0 -.03 0 1
24 0 0 0 0 1 6
24 1 -.03 .03 -.03 .03
24 4 .1  .16  .01  0.  0.      PLIMS
  24 5 .35  .25  .12  .20  0  SIZ13
1 .02 .03 .005 .03 0 0 .13
16 29 -1
21 -8 -6 6
16 16 .098
-13 5 POLYG
13 2
3 1
5.01 .5 -2. 1.  $ RADIATION HARDEND QUADRUPOLE
3 .2
5.01 .282 5 1
3 .4
16 21 0 $ INPUT 4 L B N
16 4 .098
16 5 .076
2 20
4 .291 .527 0 $  40 DEGREE PATI-JANE
4 .291 .527 0 $  PRHO=.83 METERS
2 20
3 .4
5 .282 -5 1
3 .06
5 .282 5 1
3 .20 $  REMOVE ONE QUAD FOR INTERMEADIATE FOUCS
6 4 .1 .1
10 -1 2 0 .001
10 -1 2 0 .001 CON
10 -3 4 0 .001 CON
10 -3 4 0 .001
13 1
13 4
13 7 SPECPI
SENTINEL
POLYGONS FIRST PART OF SYSTEM
 2
FIX
A POLYG 1 13
5

SENTINEL
ADD 2 ND PART OF SYSTEM     MUON COLLECTOR
2
A POLYG 1 -13
ALTER SPECPI,2,2
A PLIMS 3 .12 .14 .002
A SIZ13 3  .25  .15  .05  .16

3 .2
5 .282 -5 1
3 .06
5 .282 5 1
3 .06
5 .282 -5 1
3 .75
16 4 .16
16 5 .1
4 .39 -.63 0 $  75 DEGREES CAL TECHK
4 .39 -.63 0  $ PRHO=.595 METERS
3 .75
5.01 .282 -5 1
3 .06
3. 0.282 LXQ $ ORIGINALLY 0.06 METERS
5.01 .282 5 1
3 .4
6 4 .1 .1
10 -1 2 0 .001
10 -3 4 0 .001
13 1
13 4
13 7 SPECMU
3 .8
SENTINEL
POLYGON CALCULATION FOR PION CHANNEL
2
FIX
A POLYG 1 13
 5

SENTINEL
SENTINEL
```

Fig. 5-7. Data input to TRANSPORT for study of pion-muon spectrum. Note blank cards in the data deck reproduced here as a blank line. These blank cards could have equally well been replaced by a zero punch. The double sentinel at the end specifies the end of all data input.

```
DATE=6/18/74                                                                                                                    CASE NUMBER   1-  0-C

130 MEV/C PION CHANNEL
  (FIT,       1.596E-01)
 .000
-1.197   .000

   1(UNIT1 )      15.0        6.0                    0.0
   5(UNIT2 )      15.0        1.0        M         100.0
   9(UNIT3 )      15.0        2.0        RAD      1000.0
  13(UNIT4 )      15.0        5.0        M         100.0
  17(UNIT5 )      15.0        8.0        M           1.0
  21(UNIT6 )      15.0        9.0        T          10.0
  25(UNIT7 )      15.0       11.0        GEV         1.0
  29(VEC1  )   22.000000    6.000000
               22.000000    0.000000    0.000000    0.000000    0.000000    0.000000    0.000000   -0.000000
               22.000000    0.000000    0.000000    0.000000    0.000000    0.000000    1.000000   -0.000000
               22.000000     .020000    0.000000     .005000    0.000000    0.000000    1.000000   -0.000000
               22.000000    0.000000     .030000    0.000000     .030000    0.000000    1.000000   -0.000000
               22.000000    -.020000    0.000000    -.005000    0.000000    0.000000    1.000000   -0.000000
               22.000000    0.000000    -.030000    0.000000    -.030000    0.000000    1.000000   -0.000000
  31(PLOT1 )   24.000000    0.000000    0.000000    0.000000    0.000000    1.000000    6.000000
  38(PLOT2 )   24.000000    1.000000    -.030000     .030000    -.030000     .030000   -0.000000
  45(PLIMS )   24.000000    4.000000     .100000     .160000     .010000    0.000000    0.000000
  52(SIZ13 )   24.000000    5.000000     .350000     .250000     .120000     .200000    0.000000
  59(BEAM1 )    1.000000     .020000     .030000     .005000     .030000    0.000000    0.000000     .130000
  67(DA1   )   16.000000   29.000000   -1.000000
  70(STRY1 )   21.000000   -8.000000   -6.000000    6.000000
  74(DA2   )   16.000000   16.000000     .098000
  77(POLYG )  -13.000000    5.000000
  79(IO1   )   13.000000    2.000000
  81(L1    )    3.000000    1.000000
  83(Q1    )    5.010000     .500000   -2.088108    1.000000
  87(L2    )    3.000000     .200000
  89(Q2    )    5.010000     .282000    2.885813    1.000000
  93(L3    )    3.000000     .400000
  95(DA3   )   16.000000   21.000000    0.000000
  98(DA4   )   16.000000    4.000000     .098000
 101(DA5   )   16.000000    5.000000     .076000
 104(FF1   )    2.000000   20.000000   -0.000000
 107(BM1   )    4.000000     .291000     .527000    0.000000
 111(BM2   )    4.000000     .291000     .527000    0.000000
 115(FF2   )    2.000000   20.000000   -0.000000
 118(L4    )    3.000000     .400000
 120(Q3    )    5.000000     .282000   -5.000000    1.000000
 124(L5    )    3.000000     .060000
 126(Q4    )    5.000000     .282000    5.000000    1.000000
 130(L6    )    3.000000     .200000
 132(SLIT1 )    6.000000    4.000000     .100000     .100000
 136(CON1  )   10.000000   -1.000000    2.000000    0.000000     .001000
 141(CON   )   10.000000   -1.000000    2.000000    0.000000     .001000
 146(CON   )   10.000000   -3.000000    4.000000    0.000000     .001000
 151(CON2  )   10.000000   -3.000000    4.000000    0.000000     .001000
 156(IO2   )   13.000000    1.000000
 158(IO3   )   13.000000    4.000000
 160(SPECPI)   13.000000    7.000000

UNIT(1)=  2.998E-01  1.000E+00  2.998E-01  1.000E+00  2.998E-01  1.000E-02  1.000E+00  2.998E-01  1.000E+00  5.108E-04  1.000E+00
                                                      ..X(M  )..  .XP(RAD)..  ..Y(M  )..  .YP(RAD)..  ..S(M  )..  .DP(PC )..  ....COM
                                          VECTOR  1(A)   0.          0.          0.          0.          0.          0.         -0.0000
                                          VECTOR  2(B)   0.          0.          0.          0.          0.         1.000E+00  -0.0000
                                          VECTOR  3(C)   2.000E-02   0.          5.000E-03   0.          0.         1.000E+00  -0.0000
                                          VECTOR  4(D)   0.          3.000E-02   0.          3.000E-02   0.         1.000E+00  -0.0000
                                          VECTOR  5(E)  -2.000E-02   0.         -5.000E-03   0.          0.         1.000E+00  -0.0000
                                          VECTOR  6(F)   0.         -3.000E-02   0.         -3.000E-02   0.         1.000E+00  -0.0000
PLOTS 24.0          0    0.0000 M      0.0000 M      0.0000 M       1.0000     6.0000
PLOTS 24.0          1    -.0300 M       .0300 RAD    -.0300 M        .0300    -0.0000
PLOTS 24.0          4     .1000 GEV     .1600 GEV     .0100 GEV     0.0000     0.0000
PLOTS 24.0          5     .3500 M       .2500 RAD     .1200 M        .2000     0.0000
BEAM  1.000000     .13000 GEV                                                                                          BEAM1 - 59
                                                                    0.000     .020 M                LENGTH=    0.000 M
                                                                    0.000     .030 RAD    0.000
                                                                    0.000     .005 M      0.000 0.000
                                                                    0.000     .030 RAD    0.000 0.000 0.000
                                                                    0.000    0.000 M      0.000 0.000 0.000 0.000
                                                                    0.000    0.000 PC     0.000 0.000 0.000 0.000 0.000
                                                      ..X(M  )..  .XP(RAD)..  ..Y(M  )..  .YP(RAD)..  ..S(M  )..  .DP(PC )..  ....COM
                                          VECTOR  1(A)   0.          0.          0.          0.          0.         -0.0000
                                          VECTOR  2(B)   0.          0.          0.          0.          0.         1.000E+00  -0.0000
                                          VECTOR  3(C)   2.000E-02   0.          5.000E-03   0.          0.         1.000E+00  -0.0000
                                          VECTOR  4(D)   0.          3.000E-02   0.          3.000E-02   0.         1.000E+00  -0.0000
                                          VECTOR  5(E)  -2.000E-02   0.         -5.000E-03   0.          0.         1.000E+00  -0.0000
                                          VECTOR  6(F)   0.         -3.000E-02   0.         -3.000E-02   0.         1.000E+00  -0.0000
PAR  16.0   ( 29.0)        -1.00000
E21 21.0   -8.0   -6.0000    6.0000                                                                                   STRY1 - 70
PAR  16.0   ( 16.0)         .09800
DRIFT 3.0    1.000 M                                                    A-TABLE NO.= 2     LENGTH=    1.000 M    L1    - 81
QUAD  5.01    .500 M    -2.0881 T    1.00 M    (   -.34 M  )           A-TABLE NO.= 3     LENGTH=    1.500 M    Q1    - 83
DRIFT 3.0     .200 M                                                    A-TABLE NO.= 4     LENGTH=    1.700 M    L2    - 87
QUAD  5.01    .282 M     2.8858 T    1.00 M    (    .58 M  )           A-TABLE NO.= 5     LENGTH=    1.982 M    Q2    - 89
DRIFT 3.0     .400 M                                                    A-TABLE NO.= 6     LENGTH=    2.382 M    L3    - 93
PAR  16.0   ( 21.0)         0.00000
PAR  16.0   (  4.0)         .09800
PAR  16.0   (  5.0)         .07600
```

Fig. 5-8. Transport output generated by the option 0 data of example 2.
(Fig. 8-continued next page)

(Fig. 8-continued)

```
RORAT 2.0   20.000 D    -0.00 T                                  A-TABLE NO.= 7     LENGTH=   2.382 M    FF1   -104
BEND  4.000   .291 M      .527 T      .00   (  20.263 D)         A-TABLE NO.= 7     LENGTH=   2.673 M    BM1   -107
                                            (     .823 M  )
BEND  4.000   .291 M      .527 T      .00   (  20.263 D)         A-TABLE NO.= 8     LENGTH=   2.964 M    BM2   -111
                                            (     .823 M  )
RORAT 2.0   20.000 D    -0.00 T                                  A-TABLE NO.= 9     LENGTH=   2.964 M    FF2   -115
DRIFT 3.0     .400 M                                             A-TABLE NO.= 9     LENGTH=   3.364 M    L4    -118
QUAD  5.00    .282 M   -5.0000 T    1.00 M    (   -.27 M  )      A-TABLE NO.=10     LENGTH=   3.646 M    Q3    -120
DRIFT 3.0     .060 M                                             A-TABLE NO.=11     LENGTH=   3.706 M    L5    -124
QUAD  5.00    .282 M    5.0000 T    1.00 M    (    .36 M  )      A-TABLE NO.=12     LENGTH=   3.988 M    Q4    -126
DRIFT 3.0     .200 M                                             A-TABLE NO.=13     LENGTH=   4.188 M    L6    -130
SLIT  6.0     4     .1000 M      .1000 M                         A-TABLE NO.=14     LENGTH=   4.188 M    SLIT1 -132
FIT  10.0    -1  2   0.000000/  .001000
                      .000178
FIT  10.0    -1  2   0.000000/  .001000
                      .000178
FIT  10.0    -3  4   0.000000/  .001000
                      .000138
FIT  10.0    -3  4   0.000000/  .001000
                      .000138
```

```
                                                 0.000    .013 M                    LENGTH=    4.188 M
                                                 0.000    .045 RAD   -.013
                                                 0.000    .007 M     0.000 0.000
                                                 0.000    .036 RAD   0.000 0.000  .792
                                                 0.000    .052 M      .370  .924 0.000 0.000
                                                 0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
                                        ..X(M  )..  .XP(RAD)..  ..Y(M  )..  .YP(RAD)..  ..S(M  )..  .DP(PC )..  ....COM
VECTOR  1(A)   0.          0.          0.          0.          0.          0.          -0.0000
VECTOR  2(B)   1.076E-02  -1.503E-02   0.          0.         -4.733E-04   1.000E+00  -0.0000
VECTOR  3(C)  -2.523E-03  -1.446E-02   6.786E-03   2.870E-02  -1.983E-02   1.000E+00  -0.0000
VECTOR  4(D)   1.077E-02  -6.019E-02   4.151E-06   2.212E-02  -4.907E-02   1.000E+00  -0.0000
VECTOR  5(E)   2.405E-02  -1.560E-02  -6.786E-03  -2.870E-02   1.888E-02   1.000E+00  -0.0000
VECTOR  6(F)   1.076E-02   3.014E-02  -4.151E-06  -2.212E-02   4.812E-02   1.000E+00  -0.0000
TRANSFORM 1

     -6.6424E-01  1.7823E-04  0.          0.          0.          1.0762E-02
      2.8464E-02 -1.5055E+00  0.          0.          0.         -1.5030E-02
      0.          0.          1.3572E+00  1.3838E-04  0.          0.
      0.          0.          5.7396E+00  7.3742E-01  0.          0.
     -9.6769E-01 -1.6199E+00  0.          0.          1.0000E+00 -4.7329E-04
      0.          0.          0.          0.          0.          1.0000E+00
LENGTH   4.188M
```

J	TYPE.III	L	APH	APV	H-BEAM	V-BEAM	H-CENT	V-CENT	HRAY1	VRAY1		
1	1.059	0.0000			2.0000E-02	5.0000E-03	0.	0.	0.	0.	1	1.059-BEAM1
2	3.081	1.0000			3.6056E-02	3.0414E-02	0.	0.	0.	0.	2	3.081-L1
3	5.083	1.5000	9.8000E-02	9.8000E-02	7.5839E-02	2.5950E-02	0.	0.	0.	0.	3	5.083-Q1
4	3.087	1.7000			.1057	1.6872E-02	0.	0.	0.	0.	4	3.087-L2
5	5.089	1.9820	9.8000E-02	9.8000E-02	.1174	8.1440E-03	0.	0.	0.	0.	5	5.089-Q2
6	3.093	2.3820			8.9580E-02	7.4343E-03	0.	0.	0.	0.	6	3.093-L3
7	4.107	2.6730	9.8000E-02	7.6000E-02	7.5519E-02	1.2831E-02	0.	0.	0.	0.	7	4.107-BM1
8	4.111	2.9640	9.8000E-02	7.6000E-02	5.2189E-02	1.9353E-02	0.	0.	0.	0.	8	4.111-BM2
9	3.118	3.3640			2.4674E-02	2.6479E-02	0.	0.	0.	0.	9	3.118-L4
10	5.120	3.6460	9.8000E-02	9.8000E-02	1.7088E-02	1.9657E-02	0.	0.	0.	0.	10	5.120-Q3
11	3.124	3.7060			1.7892E-02	1.5901E-02	0.	0.	0.	0.	11	3.124-L5
12	5.126	3.9880	9.8000E-02	9.8000E-02	1.6162E-02	4.5425E-03	0.	0.	0.	0.	12	5.126-Q4
13	3.130	4.1880			1.3285E-02	6.7858E-03	0.	0.	0.	0.	13	3.130-L6
14	6.132	4.1880	1.0000E-01	1.0000E-01	1.3285E-02	6.7858E-03	0.	0.	0.	0.	14	6.132-SLIT1

J	TYPE.III	L	HRAY2	VRAY2	HRAY3	VRAY3	HRAY4	VRAY4	HRAY5	VRAY5	HRAY6	VRAY6
1	1.059	0.0000	0.	0.	2.0000E-02	5.0000E-03	0.	0.	-2.0000E-02	-5.0000E-03	0.	0.
2	3.081	1.0000	0.	0.	2.0000E-02	5.0000E-03	3.0000E-02	3.0000E-02	-2.0000E-02	-5.0000E-03	-3.0000E-02	-3.0000E-02
3	5.083	1.5000	0.	0.	3.3296E-02	2.2805E-03	6.8140E-02	2.5849E-02	-3.3296E-02	-2.2805E-03	-6.8140E-02	-2.5849E-02
4	3.087	1.7000	0.	0.	4.4978E-02	3.2758E-04	9.5652E-02	1.6868E-02	-4.4978E-02	-3.2758E-04	-9.5652E-02	-1.6868E-02
5	5.089	1.9820	0.	0.	4.8650E-02	-2.5848E-03	.1069	7.7229E-03	-4.8650E-02	2.5848E-03	-.1069	-7.7229E-03
6	3.093	2.3820	0.	0.	3.5236E-02	-7.3022E-03	8.2359E-02	-1.3949E-03	-3.5236E-02	7.3022E-03	-8.2359E-02	1.3949E-03
7	4.107	2.6730	5.0923E-04	0.	2.8451E-02	-1.0104E-02	7.0669E-02	-7.9078E-03	-2.7432E-02	1.0104E-02	-6.9651E-02	7.9078E-03
8	4.111	2.9640	1.9739E-03	0.	1.9162E-02	-1.2906E-02	5.1251E-02	-1.4421E-02	-1.5214E-02	1.2906E-02	-4.7304E-02	1.4421E-02
9	3.118	3.3640	4.9223E-03	0.	8.5639E-03	-1.5227E-02	2.9326E-02	-2.1663E-02	1.2808E-03	1.5227E-02	-1.9401E-02	2.1663E-02
10	5.120	3.6460	9.7681E-03	0.	4.1328E-03	-1.0161E-02	2.5901E-02	-1.6828E-02	1.5403E-02	1.0161E-02	-6.3644E-03	1.6828E-02
11	3.124	3.7060	1.1543E-02	0.	3.6949E-03	-7.8239E-03	2.7622E-02	-1.3843E-02	1.9391E-02	7.8239E-03	-4.5358E-03	1.3843E-02
12	5.126	3.9880	1.3768E-02	0.	3.6903E-04	1.0462E-03	2.2806E-02	-4.4204E-03	2.7166E-02	-1.0462E-03	4.7294E-03	4.4204E-03
13	3.130	4.1880	1.0762E-02	0.	-2.5230E-03	6.7858E-03	1.0767E-02	4.1513E-06	2.4047E-02	-6.7858E-03	1.0756E-02	-4.1513E-06
14	6.132	4.1880	1.0762E-02	0.	-2.5230E-03	6.7858E-03	1.0767E-02	4.1513E-06	2.4047E-02	-6.7858E-03	1.0756E-02	-4.1513E-06

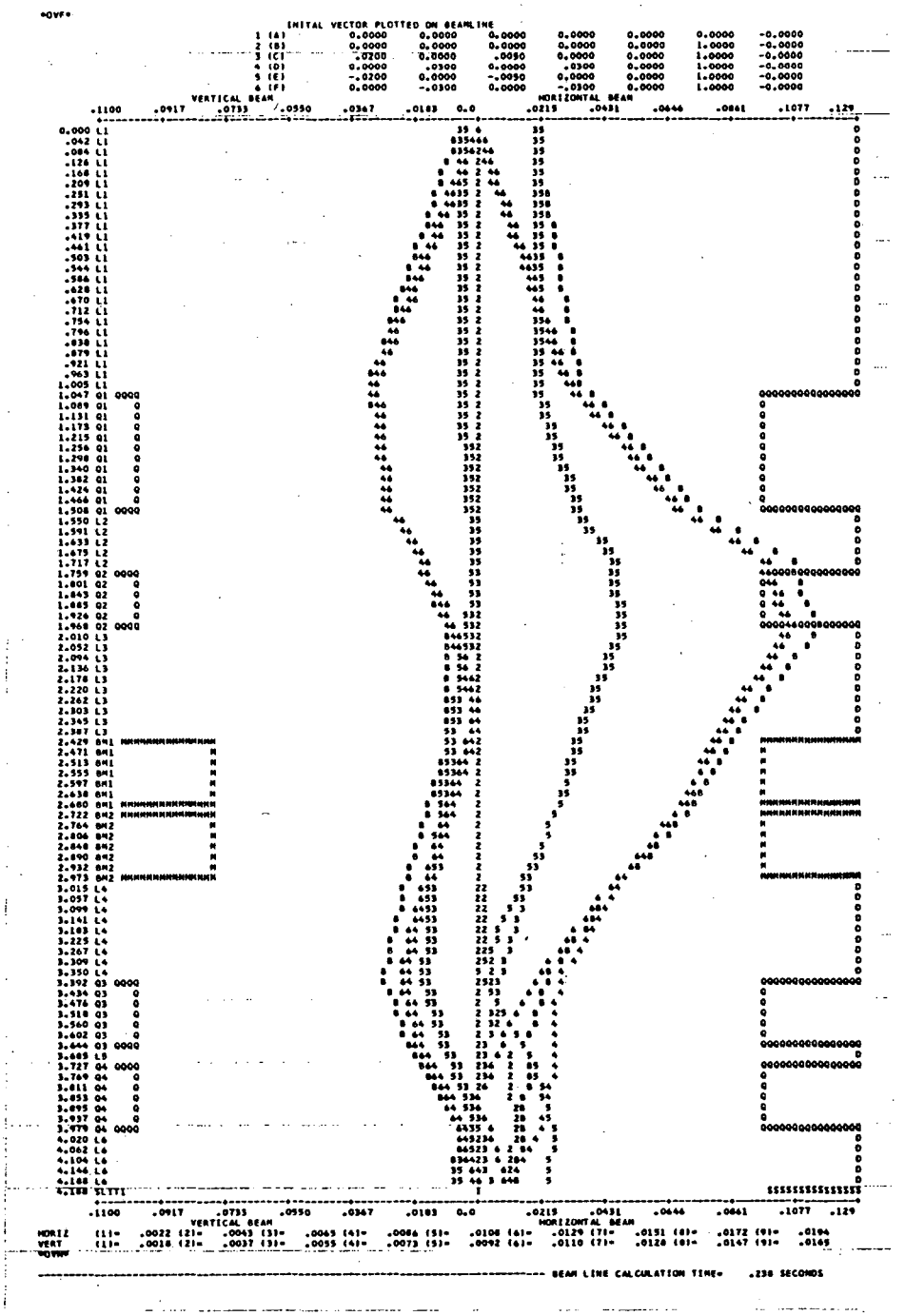


Fig. 5-9. Beam line graph of the PION collector, first half of the π-μ channel.

```
DATE=6/18/74                                                                                    CASE NUMBER   2-  0

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
POLYGONS FIRST PART OF SYSTEM
 2
FIX
A POLYG 1 13
5

SENTINEL

PHASE SPACE APERATURE TRANSFORMATION AT LOCATION OF 13.5.0 MOMENTUM DEVIATION =  -0.0000 PC        P=    .1300 GEV

                          /----HORIZONTAL POLYGON VERTICES---/     /----VERTICAL POLYGON VERTICES-----/
                                X       XPRIME      TAG1      TAG2      Y       YPRIME      TAG1      TAG2
                        1     -.1025     .0974    5.126  Q4            .0194     .0538    5.120  Q3
                        2     -.1214     .0554    5.089  Q2            .0117     .0863    5.083  Q1
                        3      .1025    -.0974    5.126  Q4           -.0334     .1314    5.083  Q1
                        4      .1214    -.0554    5.089  Q2           -.0562     .1435    2.115  FF2
                        5                                            -.0194    -.0538    5.120  Q3
                        6                                            -.0117    -.0863    5.083  Q1
                        7                                             .0334    -.1314    5.083  Q1
                        8                                             .0562    -.1435    2.115  FF2

HORIZONTAL/  POLYGON AREA=     1.2313E-02 M  RAD  CENTER LOCATED AT    1.1102E-16 M   -1.1102E-16 RAD

VERTICAL  /  POLYGON AREA=     1.3863E-02 M  RAD  CENTER LOCATED AT    2.7756E-17 M   -3.3307E-16 RAD

          POLYGON AREA SUBTENDED BY TARGET

TARGET AREA SOLID ANGLE=       9.6776E+00 MSR

HORIZONTAL/  POLYGON AREA=     3.3003E-03 M  RAD  AVE. ANGULAR ACCEPTANCE=       5.5005E-02 RAD

VERTICAL  /  POLYGON AREA=     1.0556E-02 M  RAD  AVE. ANGULAR ACCEPTANCE=       1.7594E-01 RAD

MATRIX
       -6.6424E-01  1.7823E-04  0.          0.          0.          1.0762E-02
        2.8464E-02 -1.5055E+00  0.          0.          0.         -1.5030E-02
        0.          0.          1.3572E+00  1.3838E-04  0.          0.
        0.          0.          5.7396E+00  7.3742E-01  0.          0.
       -9.6769E-01 -1.6199E+00  0.          0.          1.0000E+00 -4.7329E-04
        0.          0.          0.          0.          0.          1.0000E+00
```

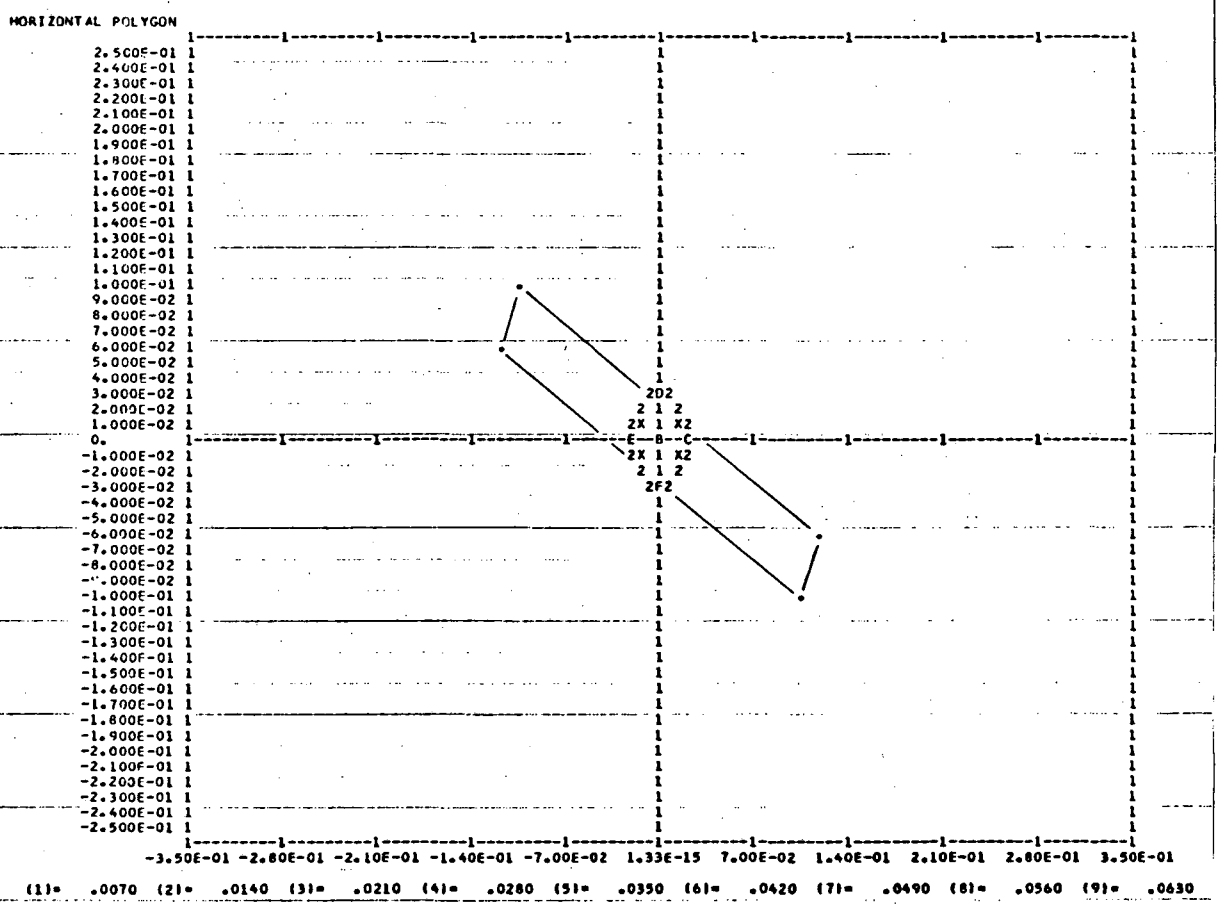
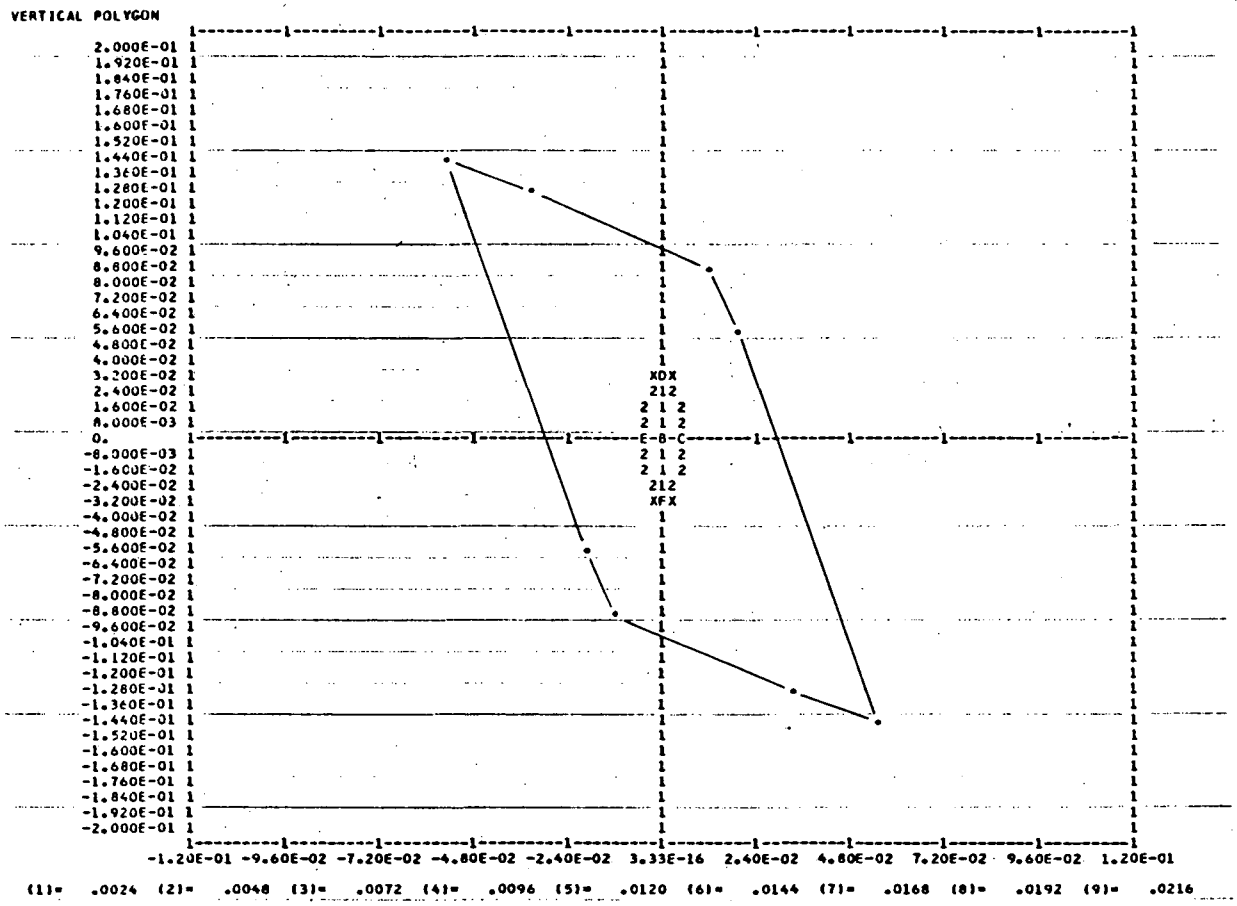


Fig. 5-10. Polygon calculation output showing the PI channel acceptance for example 2. The dot's are the polygon vertices and the x's are the beam ellipse.

(Fig. 10 -continued)



```
DATE=6/18/74                                                                                                                    CASE NUMBER   3-  0-C

ADD 2 ND PART OF SYSTEM    MUON COLLECTOR
   (FIT,        2.916E+02)
   .001
   .471    .002


     1(UNIT1 )        15.0        6.0                    0.0
     5(UNIT2 )        15.0        1.0        M         100.0
     9(UNIT3 )        15.0        2.0        RAD      1000.0
    13(UNIT4 )        15.0        5.0        M         100.0
    17(UNIT5 )        15.0        8.0        M           1.0
    21(UNIT6 )        15.0        9.0        T          10.0
    25(UNIT7 )        15.0       11.0        GEV         1.0
    29(VEC1  )    22.000000    6.000000
                  22.000000    0.000000    0.000000    0.000000    0.000000    0.000000    0.000000   -0.000000
                  22.000000    0.000000    0.000000    0.000000    0.000000    0.000000    1.000000   -0.000000
                  22.000000     .020000    0.000000     .005000    0.000000    0.000000    1.000000   -0.000000
                  22.000000    0.000000     .030000    0.000000     .030000    0.000000    1.000000   -0.000000
                  22.000000   -.020000    0.000000    -.005000    0.000000    0.000000    1.000000   -0.000000
                  22.000000    0.000000    -.030000    0.000000    -.030000    0.000000    1.000000   -0.000000
    31(PLOT1 )    24.000000    0.000000    0.000000    0.000000    0.000000    1.000000    6.000000
    38(PLOT2 )    24.000000    1.000000    -.030000     .030000    -.030000     .030000   -0.000000
    45(PLIMS )    24.000000    4.000000     .120000     .140000     .002000    0.000000    0.000000
    52(SIZ13 )    24.000000    5.000000     .250000     .150000     .050000     .160000    0.000000
    59(BEAM1 )     1.000000     .020000     .030000     .005000     .030000    0.000000    0.000000     .130000
    67(DA1   )    16.000000   29.000000   -1.000000
    70(STRY1 )    21.000000   -8.000000   -6.000000    6.000000
    74(DA2   )    16.000000   16.000000     .098000
    77(POLYG )   -13.000000    5.000000
    79(I01   )    13.000000    2.000000
    81(L1    )     3.000000    1.000000
    83(Q1    )     5.000000     .500000   -2.088108    1.000000
    87(L2    )     3.000000     .200000
    89(Q2    )     5.000000     .282000    2.885813    1.000000
    93(L3    )     3.000000     .400000
    95(DA3   )    16.000000   21.000000    0.000000
    98(DA4   )    16.000000    4.000000     .098000
   101(DA5   )    16.000000    5.000000     .076000
   104(FF1   )     2.000000   20.000000   -0.000000
   107(BM1   )     4.000000     .291000     .527000    0.000000
   111(BM2   )     4.000000     .291000     .527000    0.000000
   115(FF2   )     2.000000   20.000000   -0.000000
   118(L4    )     3.000000     .400000
   120(Q3    )     5.000000     .282000   -5.000000    1.000000
   124(L5    )     3.000000     .060000
   126(Q4    )     5.000000     .282000    5.000000    1.000000
   130(L6    )     3.000000     .200000
   132(SLIT1 )     6.000000    4.000000     .100000     .100000
   136(CON1  )   -10.000000   -1.000000    2.000000    0.000000     .001000
   141(CON   )   -10.000000   -1.000000    2.000000    0.000000     .001000
   146(CON   )   -10.000000   -3.000000    4.000000    0.000000     .001000
   151(CON2  )   -10.000000   -3.000000    4.000000    0.000000     .001000
   156(I02   )    13.000000    1.000000
   158(I03   )    13.000000    4.000000
   160(SPECPI)    13.000000    2.000000
   162(L7    )     3.000000     .200000
   164(Q5    )     5.000000     .282000   -5.000000    1.000000
   168(L8    )     3.000000     .060000
   170(Q6    )     5.000000     .282000    5.000000    1.000000
   174(L9    )     3.000000     .060000
   176(Q7    )     5.000000     .282000   -5.000000    1.000000
   180(L10   )     3.000000     .750000
   182(DA6   )    16.000000    4.000000     .160000
   185(DA7   )    16.000000    5.000000     .100000
   188(BM3   )     4.000000     .390000    -.630000    0.000000
   192(BM4   )     4.000000     .390000    -.630000    0.000000
   196(L11   )     3.000000     .750000
   198(Q8    )     5.010000     .282000   -3.203835    1.000000
   202(L12   )     3.000000     .060000
   204(LXQ   )     3.000000     .282000
   206(Q9    )     5.010000     .282000    5.999515    1.000000
   210(L13   )     3.000000     .400000
   212(SLIT2 )     6.000000    4.000000     .100000     .100000
   216(CON3  )    10.000000   -1.000000    2.000000    0.000000     .001000
   221(CON4  )    10.000000   -3.000000    4.000000    0.000000     .001000
   226(I04   )    13.000000    1.000000
   228(I05   )    13.000000    4.000000
   230(SPECMU)    13.000000    7.000000
   232(L14   )     3.000000     .800000
```

Fig. 5-11. Transport output for the complete π-μ channel of example 2.

(Fig. 11 -continued)

```
UNIT()=  2.998E-01  1.000E+00  2.998E-01  1.000E+00  2.998E-01  1.000E-02  1.000E+00  2.998E-01  1.000E+00  5.108E-04  1.000E+00
                                                        ..X(M   ).. .XP(RAD).. ..Y(M   ).. .YP(RAD).. ..S(M   ).. .DP(PC )..  ....COM
                                         VECTOR  1(A)   0.          0.          0.          0.          0.          0.          -0.0000
                                         VECTOR  2(B)   0.          0.          0.          0.          0.          1.000E+00  -0.0000
                                         VECTOR  3(C)   2.000E-02   0.          5.000E-03   0.          0.          1.000E+00  -0.0000
                                         VECTOR  4(D)   0.          3.000E-02   0.          3.000E-02   0.          1.000E+00  -0.0000
                                         VECTOR  5(E)  -2.000E-02   0.         -5.000E-03   0.          0.          1.000E+00  -0.0000
                                         VECTOR  6(F)   0.         -3.000E-02   0.         -3.000E-02   0.          1.000E+00  -0.0000
PLOTS 24.0          0     0.0000 M      0.0000 M      0.0000 M      1.0000    6.0000
PLOTS 24.0          1     -.0300 M      .0300 RAD     -.0300 M      .0300    -0.0000
PLOTS 24.0          4      .1200 GEV    .1400 GEV      .0020 GEV    0.0000    0.0000
PLOTS 24.0          5      .2500 M      .1500 RAD      .0500 M      .1600    0.0000
BEAM  1.000000      .13000 GEV                        ------------------------------------------------------------ BEAM1 - 59
                                                                    0.000     .020 M                    LENGTH=   0.000 M
                                                                    0.000     .030 RAD   0.000
                                                                    0.000     .005 M     0.000 0.000
                                                                    0.000     .030 RAD   0.000 0.000 0.000
                                                                    0.000    0.000 M     0.000 0.000 0.000 0.000
                                                                    0.000    0.000 PC    0.000 0.000 0.000 0.000 0.000
                                                        ..X(M   ).. .XP(RAD).. ..Y(M   ).. .YP(RAD).. ..S(M   ).. .DP(PC )..  ....COM
                                         VECTOR  1(A)   0.          0.          0.          0.          0.          0.          -0.0000
                                         VECTOR  2(B)   0.          0.          0.          0.          0.          1.000E+00  -0.0000
                                         VECTOR  3(C)   2.000E-02   0.          5.000E-03   0.          0.          1.000E+00  -0.0000
                                         VECTOR  4(D)   0.          3.000E-02   0.          3.000E-02   0.          1.000E+00  -0.0000
                                         VECTOR  5(E)  -2.000E-02   0.         -5.000E-03   0.          0.          1.000E+00  -0.0000
                                         VECTOR  6(F)   0.         -3.000E-02   0.         -3.000E-02   0.          1.000E+00  -0.0000
PAR  16.0    ( 29.0)       -1.00000
E21 21.0   -8.0   -6.0000   6.0000                    ------------------------------------------------------------ STRY1 - 70
PAR  16.0    ( 16.0)        .09800
DRIFT 3.0    1.000 M                                                  A-TABLE NO.= 2    LENGTH=    1.000 M   L1     - 81
QUAD  5.00    .500 M    -2.0881 T    1.00 M    (   -.34 M  )          A-TABLE NO.= 3    LENGTH=    1.500 M   Q1     - 83
DRIFT 3.0     .200 M                                                  A-TABLE NO.= 4    LENGTH=    1.700 M   L2     - 87
QUAD  5.00    .282 M     2.8858 T    1.00 M    (    .58 M  )          A-TABLE NO.= 5    LENGTH=    1.982 M   Q2     - 89
DRIFT 3.0     .430 M                                                  A-TABLE NO.= 6    LENGTH=    2.382 M   L3     - 93
PAR  16.0    ( 21.0)        0.00000
PAR  16.0    (  4.0)         .09800
PAR  16.0    (  5.0)         .07600
RORAT 2.0    20.000 D    -0.00 T                                      A-TABLE NO.= 7    LENGTH=    2.382 M   FF1    -104
BEND  4.000   .291 M      .527 T      .00    (  20.263 D)             A-TABLE NO.= 7    LENGTH=    2.673 M   BM1    -107
                                             (    .823 M  )
BEND  4.000   .291 M      .527 T      .00    (  20.263 D)             A-TABLE NO.= 8    LENGTH=    2.964 M   BM2    -111
                                             (    .823 M  )
RORAT 2.0    20.000 D    -0.00 T                                      A-TABLE NO.= 9    LENGTH=    2.964 M   FF2    -115
DRIFT 3.0     .400 M                                                  A-TABLE NO.= 9    LENGTH=    3.364 M   L4     -118
QUAD  5.00    .282 M    -5.0000 T    1.00 M    (   -.27 M  )          A-TABLE NO.=10    LENGTH=    3.646 M   Q3     -120
DRIFT 3.0     .060 M                                                  A-TABLE NO.=11    LENGTH=    3.706 M   L5     -124
QUAD  5.00    .282 M     5.0000 T    1.00 M    (    .36 M  )          A-TABLE NO.=12    LENGTH=    3.988 M   Q4     -126
DRIFT 3.0     .200 M                                                  A-TABLE NO.=13    LENGTH=    4.188 M   L6     -130
SLIT  6.0    4    .1000 M      .1000 M                                A-TABLE NO.=14    LENGTH=    4.188 M   SLIT1 -132
                                                                    0.000     .013 M                LENGTH=    4.188 M
                                                                    0.000     .045 RAD   -.013
                                                                    0.000     .007 M     0.000 0.000
                                                                    0.000     .036 RAD   0.000 0.000  .792
                                                                    0.000     .052 M      .370  .924 0.000 0.000
                                                                    0.000    0.000 PC    0.000 0.000 0.000 0.000 0.000
                                                        ..X(M   ).. .XP(RAD).. ..Y(M   ).. .YP(RAD).. ..S(M   ).. .DP(PC )..  ....COM
                                         VECTOR  1(A)   0.          0.          0.          0.          0.          0.          -0.0000
                                         VECTOR  2(B)   1.076E-02  -1.503E-02   0.          0.         -4.733E-04   1.000E+00  -0.0000
                                         VECTOR  3(C)  -2.523E-03  -1.446E-02   6.786E-03   2.870E-02  -1.983E-02   1.000E+00  -0.0000
                                         VECTOR  4(D)   1.077E-02  -6.019E-02   4.151E-06   2.212E-02  -4.907E-02   1.000E+00  -0.0000
                                         VECTOR  5(E)   2.405E-02  -1.560E-02  -6.786E-03  -2.870E-02   1.888E-02   1.000E+00  -0.0000
                                         VECTOR  6(F)   1.076E-02   3.014E-02  -4.151E-06  -2.212E-02   4.812E-02   1.000E+00  -0.0000
TRANSFORM 1

      -6.6424E-01  1.7823E-04  0.           0.           0.           1.0762E-02
       2.8464E-02 -1.5055E+00  0.           0.           0.          -1.5030E-02
       0.          0.          1.3572E+00   1.3838E-04   0.           0.
       0.          0.          5.7396E+00   7.3742E-01   0.           0.
      -9.6769E-01 -1.6199E+00  0.           0.           1.0000E+00  -4.7329E-04
       0.          0.          0.           0.           0.           1.0000E+00
DRIFT 3.0     .200 M                                                  A-TABLE NO.=15    LENGTH=    4.388 M   L7     -162
QUAD  5.00    .282 M    -5.0000 T    1.00 M    (   -.27 M  )          A-TABLE NO.=16    LENGTH=    4.670 M   Q5     -164
DRIFT 3.0     .060 M                                                  A-TABLE NO.=17    LENGTH=    4.730 M   L8     -168
QUAD  5.00    .282 M     5.0000 T    1.00 M    (    .36 M  )          A-TABLE NO.=18    LENGTH=    5.012 M   Q6     -170
DRIFT 3.0     .060 M                                                  A-TABLE NO.=19    LENGTH=    5.072 M   L9     -174
QUAD  5.00    .282 M    -5.0000 T    1.00 M    (   -.27 M  )          A-TABLE NO.=20    LENGTH=    5.354 M   Q7     -176
DRIFT 3.0     .750 M                                                  A-TABLE NO.=21    LENGTH=    6.104 M   L10    -180
PAR  16.0    (  4.0)         .16000
PAR  16.0    (  5.0)         .10000
BEND  4.000   .390 M     -.630 T      .00    ( -32.464 D)             A-TABLE NO.=22    LENGTH=    6.494 M   BM3    -188
                                             (    -.688 M  )
BEND  4.000   .390 M     -.630 T      .00    ( -32.464 D)             A-TABLE NO.=23    LENGTH=    6.884 M   BM4    -192
                                             (    -.688 M  )
DRIFT 3.0     .750 M                                                  A-TABLE NO.=24    LENGTH=    7.634 M   L11    -196
QUAD  5.01    .282 M    -3.2038 T    1.00 M    (   -.44 M  )          A-TABLE NO.=25    LENGTH=    7.916 M   Q8     -198
DRIFT 3.0     .060 M                                                  A-TABLE NO.=26    LENGTH=    7.976 M   L12    -202
DRIFT 3.0     .282 M                                                  A-TABLE NO.=27    LENGTH=    8.258 M   LXQ    -204
QUAD  5.01    .282 M     5.9995 T    1.00 M    (    .31 M  )          A-TABLE NO.=28    LENGTH=    8.540 M   Q9     -206
DRIFT 3.0     .400 M                                                  A-TABLE NO.=29    LENGTH=    8.940 M   L13    -210
SLIT  6.0    4    .1000 M      .1000 M                                A-TABLE NO.=30    LENGTH=    8.940 M   SLIT2 -212
FIT  10.0    -1  2   0.000000/  .001000
                      .412325
FIT  10.0    -3  4   0.000000/  .001000
                     -.000332
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(Fig. 11 -continued)

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                                   0.000     .012 M                     LENGTH=     8.940 M
                                   0.000     .103 RAD    -.884
                                   0.000     .011 M      0.000 0.000
                                   0.000     .040 RAD    0.000 0.000  .943
                                   0.000     .219 M      -.975  .965 0.000 0.000
                                   0.000     0.000 PC    0.000 0.000 0.000 0.000 0.000
```

	..X(M)..	.XP(RAD)..	..Y(M)..	.YP(RAD)..	..S(M)..	.DP(PC)..	....COM
VECTOR 1(A)	0.	0.	0.	0.	0.	0.	-0.0000
VECTOR 2(B)	1.009E-02	9.798E-02	0.	0.	-6.261E-03	1.000E+00	-0.0000
VECTOR 3(C)	1.176E-02	3.822E-02	1.142E-02	3.733E-02	-8.292E-02	1.000E+00	-0.0000
VECTOR 4(D)	2.246E-02	1.440E-02	-9.969E-06	1.310E-02	-2.118E-01	1.000E+00	-0.0000
VECTOR 5(E)	8.427E-03	1.578E-01	-1.142E-02	-3.733E-02	7.040E-02	1.000E+00	-0.0000
VECTOR 6(F)	-2.276E-03	1.816E-01	9.969E-06	-1.310E-02	1.993E-01	1.000E+00	-0.0000

```
TRANSFORM 1

      8.3331E-02  4.1233E-01  0.          0.          0.          1.0094E-02
     -2.9884E+00 -2.7861E+00  0.          0.          0.          9.7984E-02
      0.          0.          2.2848E+00 -3.3231E-04  0.          0.

      0.          0.          7.4658E+00  4.3660E-01  0.          0.
     -3.8328E+00 -6.8523E+00  0.          0.          1.0000E+00 -6.2605E-03
      0.          0.          0.          0.          0.          1.0000E+00
DRIFT 3.0    .800 M                                        A-TABLE NO.=31    LENGTH=    9.740 M    L14   -232
LENGTH   9.740M
```

J	TYPE.III	L	APH	APV	H-BEAM	V-BEAM	H-CENT	V-CENT	HRAY1	VRAY1		
1	1.059	0.0000			2.0000E-02	5.0000E-03	0.	0.	0.	0.	1	1.059-BEAM1
2	3.081	1.0000			3.6056E-02	3.0414E-02	0.	0.	0.	0.	2	3.081-L1
3	5.083	1.5000	9.8000E-02	9.8000E-02	7.5839E-02	2.5950E-02	0.	0.	0.	0.	3	5.083-Q1
4	3.087	1.7000			.1057	1.6872E-02	0.	0.	0.	0.	4	3.087-L2
5	5.089	1.9820	9.8000E-02	9.8000E-02	.1174	8.1440E-03	0.	0.	0.	0.	5	5.089-Q2
6	3.093	2.3820			8.9580E-02	7.4343E-03	0.	0.	0.	0.	6	3.093-L3
7	4.107	2.6730	9.8000E-02	7.6000E-02	7.5519E-02	1.2831E-02	0.	0.	0.	0.	7	4.107-BM1
8	4.111	2.9640	9.8000E-02	7.6000E-02	5.2189E-02	1.9353E-02	0.	0.	0.	0.	8	4.111-BM2
9	3.118	3.3640			2.4674E-02	2.6479E-02	0.	0.	0.	0.	9	3.118-L4
10	5.120	3.6460	9.8000E-02	9.8000E-02	1.7088E-02	1.9657E-02	0.	0.	0.	0.	10	5.120-Q3
11	3.124	3.7060			1.7892E-02	1.5901E-02	0.	0.	0.	0.	11	3.124-L5
12	5.126	3.9880	9.8000E-02	9.8000E-02	1.6162E-02	4.5425E-03	0.	0.	0.	0.	12	5.126-Q4
13	3.130	4.1880			1.3285E-02	6.7858E-03	0.	0.	0.	0.	13	3.130-L6
14	6.132	4.1880	1.0000E-01	1.0000E-01	1.3285E-02	6.7858E-03	0.	0.	0.	0.	14	6.132-SLIT1
15	3.162	4.3880			1.5968E-02	1.3285E-02	0.	0.	0.	0.	15	3.162-L7
16	5.164	4.6700	9.8000E-02	9.8000E-02	3.4340E-02	1.6168E-02	0.	0.	0.	0.	16	5.164-Q5
17	3.168	4.7300			4.1032E-02	1.5234E-02	0.	0.	0.	0.	17	3.168-L8
18	5.170	5.0120	9.8000E-02	9.8000E-02	5.0645E-02	1.8024E-02	0.	0.	0.	0.	18	5.170-Q6
19	3.174	5.0720			4.7714E-02	2.0222E-02	0.	0.	0.	0.	19	3.174-L9
20	5.176	5.3540	9.8000E-02	9.8000E-02	5.5517E-02	2.0560E-02	0.	0.	0.	0.	20	5.176-Q7
21	3.180	6.1040			.1369	7.6368E-03	0.	0.	0.	0.	21	3.180-L10
22	4.188	6.4940	.1600	1.0000E-01	.1557	2.0547E-02	0.	0.	0.	0.	22	4.188-BM3
23	4.192	6.8840	.1600	1.0000E-01	.1258	3.4128E-02	0.	0.	0.	0.	23	4.192-BM4
24	3.196	7.6340			2.5493E-02	6.0471E-02	0.	0.	0.	0.	24	3.196-L11
25	5.198	7.9160	9.8000E-02	9.8000E-02	1.0570E-02	5.2543E-02	0.	0.	0.	0.	25	5.198-Q8
26	3.202	7.9760			1.7145E-02	4.7226E-02	0.	0.	0.	0.	26	3.202-L12
27	3.204	8.2580			5.0021E-02	2.2252E-02	0.	0.	0.	0.	27	3.204-LXQ
28	5.206	8.5400	9.8000E-02	9.8000E-02	5.2459E-02	6.3133E-03	0.	0.	0.	0.	28	5.206-Q9
29	3.210	8.9400			1.2482E-02	1.1424E-02	0.	0.	0.	0.	29	3.210-L13
30	6.212	8.9400	1.0000E-01	1.0000E-01	1.2482E-02	1.1424E-02	0.	0.	0.	0.	30	6.212-SLIT2
31	3.232	9.7400			7.1411E-02	4.2594E-02	0.	0.	0.	0.	31	3.232-L14

J	TYPE.III	L	HRAY2	VRAY2	HRAY3	VRAY3	HRAY4	VRAY4	HRAY5	VRAY5	HRAY6	VRAY6
1	1.059	0.0000	0.	0.	2.0000E-02	5.0000E-03	0.	0.	-2.0000E-02	-5.0000E-03	0.	0.
2	3.081	1.0000	0.	0.	2.0000E-02	5.0000E-03	3.0000E-02	3.0000E-02	-2.0000E-02	-5.0000E-03	-3.0000E-02	-3.0000E-02
3	5.083	1.5000	0.	0.	3.3296E-02	2.2805E-03	6.8140E-02	2.5849E-02	-3.3296E-02	-2.2805E-03	-6.8140E-02	-2.5849E-02
4	3.087	1.7000	0.	0.	4.4978E-02	3.2758E-04	9.5652E-02	1.6868E-02	-4.4978E-02	-3.2758E-04	-9.5652E-02	-1.6868E-02
5	5.089	1.9820	0.	0.	4.8650E-02	-2.5848E-03	.1069	7.7229E-03	-4.8650E-02	2.5848E-03	-.1069	-7.7229E-03
6	3.093	2.3820	0.	0.	3.5236E-02	-7.3022E-03	8.2359E-02	-1.3949E-03	-3.5236E-02	7.3022E-03	-8.2359E-02	1.3949E-03
7	4.107	2.6730	5.0923E-04	0.	2.8451E-02	-1.0104E-02	7.0669E-02	-7.9078E-03	-2.7432E-02	1.0104E-02	-6.9651E-02	7.9078E-03
8	4.111	2.9640	1.9739E-03	0.	1.9162E-02	-1.2906E-02	5.1251E-02	-1.4421E-02	-1.5214E-02	1.2906E-02	-4.7304E-02	1.4421E-02
9	3.118	3.3640	4.9223E-03	0.	8.5639E-03	-1.5227E-02	2.9326E-02	-2.1663E-02	1.2808E-03	1.5227E-02	-1.9481E-02	2.1663E-02
10	5.120	3.6460	9.7681E-03	0.	4.1328E-03	-1.0161E-02	2.5901E-02	-1.6828E-02	1.5403E-02	1.0161E-02	-6.3644E-03	1.6828E-02
11	3.124	3.7060	1.1543E-02	0.	3.6949E-03	-7.8239E-03	2.7622E-02	-1.3843E-02	1.9391E-02	7.8239E-03	-4.5358E-03	1.3843E-02
12	5.126	3.9880	1.3768E-02	0.	3.6903E-04	1.0462E-03	2.2806E-02	-4.4204E-03	2.7166E-02	-1.0462E-03	4.7294E-03	4.4204E-03
13	3.130	4.1880	1.0762E-02	0.	-2.5230E-03	6.7858E-03	1.0767E-02	4.1513E-06	2.4047E-02	-6.7858E-03	1.0756E-02	-4.1513E-06
14	6.132	4.1880	1.0762E-02	0.	-2.5230E-03	6.7858E-03	1.0767E-02	4.1513E-06	2.4047E-02	-6.7858E-03	1.0756E-02	-4.1513E-06
15	3.162	4.3880	7.7559E-03	0.	-5.4151E-03	1.2525E-02	-1.2717E-03	4.4287E-03	2.0927E-02	-1.2525E-02	1.6783E-02	-4.4287E-03
16	5.164	4.6700	6.6755E-03	0.	-1.2824E-02	1.4120E-02	-2.1591E-02	7.8767E-03	2.6175E-02	-1.4120E-02	3.4942E-02	-7.8767E-03
17	3.168	4.7300	7.0829E-03	0.	-1.5346E-02	1.3024E-02	-2.7277E-02	7.9027E-03	2.9512E-02	-1.3024E-02	4.1443E-02	-7.9027E-03
18	5.170	5.0120	5.7116E-03	0.	-1.8956E-02	1.3490E-02	-3.8520E-02	1.1953E-02	3.0379E-02	-1.3490E-02	4.9944E-02	-1.1953E-02
19	3.174	5.0720	4.7660E-03	0.	-1.7850E-02	1.4800E-02	-3.7248E-02	1.3780E-02	2.7382E-02	-1.4800E-02	4.6780E-02	-1.3780E-02
20	5.176	5.3540	1.9675E-03	0.	-2.0653E-02	1.3773E-02	-4.8732E-02	1.5265E-02	2.4588E-02	-1.3773E-02	5.2667E-02	-1.5265E-02
21	3.180	6.1040	-2.2175E-03	0.	-5.0498E-02	-7.6313E-03	-.1303	-2.9007E-04	4.6063E-02	7.6313E-03	.1259	2.9007E-04
22	4.188	6.4940	-5.0082E-03	0.	-5.8385E-02	-1.8761E-02	-.1512	-8.3789E-03	4.8369E-02	1.8761E-02	.1412	8.3789E-03
23	4.192	6.8840	-8.3849E-03	0.	-5.0175E-02	-2.9892E-02	-.1270	-1.6468E-02	3.3405E-02	2.9892E-02	.1102	1.6468E-02
24	3.196	7.6340	-1.4763E-02	0.	-1.9775E-02	-5.1296E-02	-3.9759E-02	-3.2023E-02	-9.7512E-03	5.1296E-02	1.0232E-02	3.2023E-02
25	5.198	7.9160	-2.1957E-02	0.	-1.3291E-02	-4.4233E-02	-1.5904E-02	-2.8360E-02	-3.0622E-02	4.4233E-02	-2.8009E-02	2.8360E-02
26	3.202	7.9760	-2.4556E-02	0.	-1.2831E-02	-3.9663E-02	-1.2242E-02	-2.5634E-02	-3.6481E-02	3.9663E-02	-3.7070E-02	2.5634E-02
27	3.204	8.2580	-3.7343E-02	0.	-1.0665E-02	-1.8187E-02	4.9705E-03	-1.2821E-02	-6.4020E-02	1.8187E-02	-7.9656E-02	1.2821E-02
28	5.206	8.5400	-2.9100E-02	0.	-3.5268E-03	-3.5078E-03	1.6703E-02	-5.2491E-03	-5.4674E-02	3.5078E-03	-7.4904E-02	5.2491E-03
29	3.210	8.9400	1.0094E-02	0.	1.1760E-02	1.1424E-02	2.2463E-02	-9.9692E-06	8.4269E-03	-1.1424E-02	-2.2762E-03	9.9692E-06
30	6.212	8.9400	1.0094E-02	0.	1.1760E-02	1.1424E-02	2.2463E-02	-9.9692E-06	8.4269E-03	-1.1424E-02	-2.2762E-03	9.9692E-06
31	3.232	9.7400	8.8481E-02	0.	4.2334E-02	4.1287E-02	3.3983E-02	1.0446E-02	.1344	-4.1287E-02	.1430	-1.0446E-02

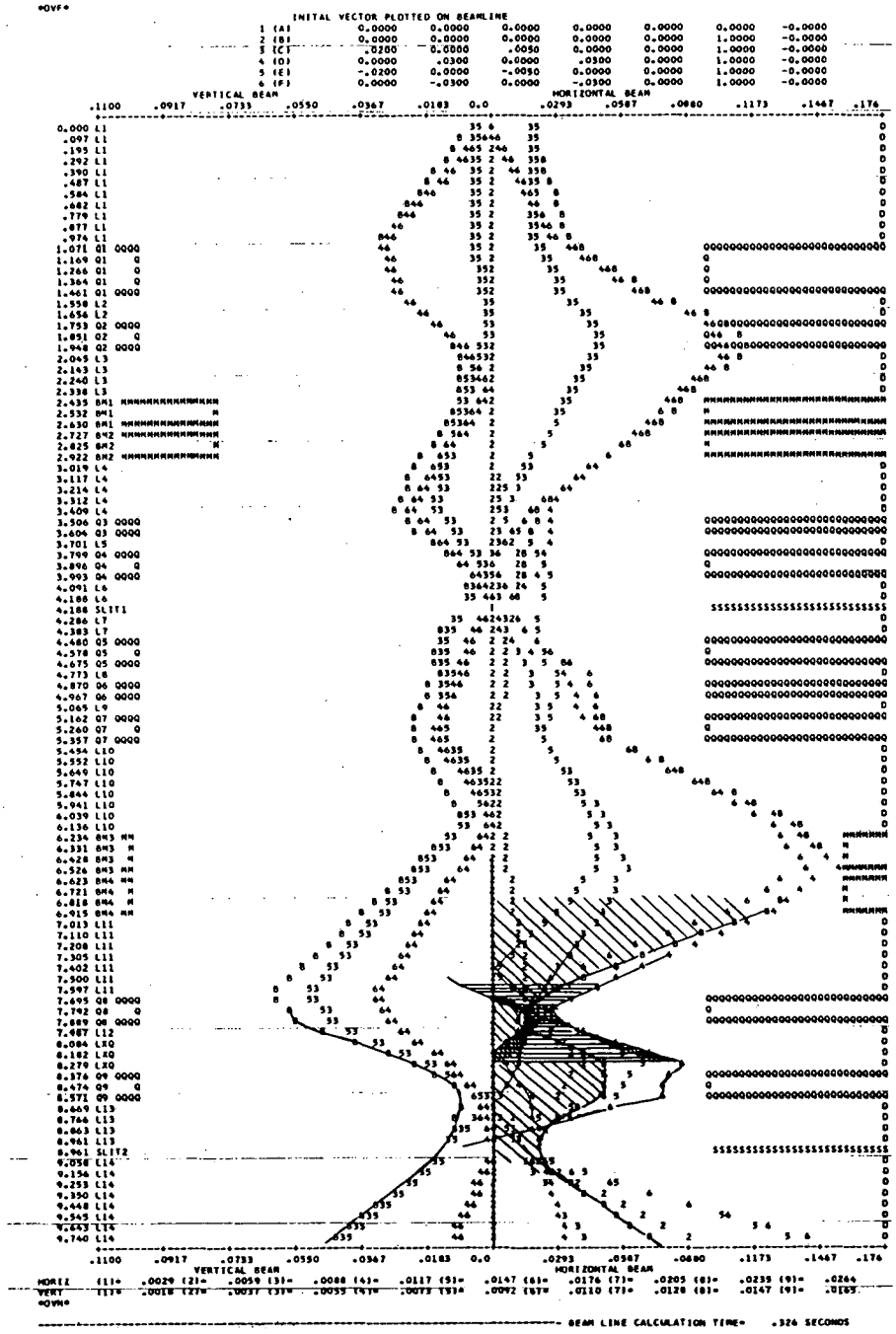

Fig. 5-12. The beam line graph of the complete π-μ channel. Vectors 2,3,4,5, and 6 represent a 1% momentum deviated beam. Note the point of maximum momentum resolution after quadrupole Q8.

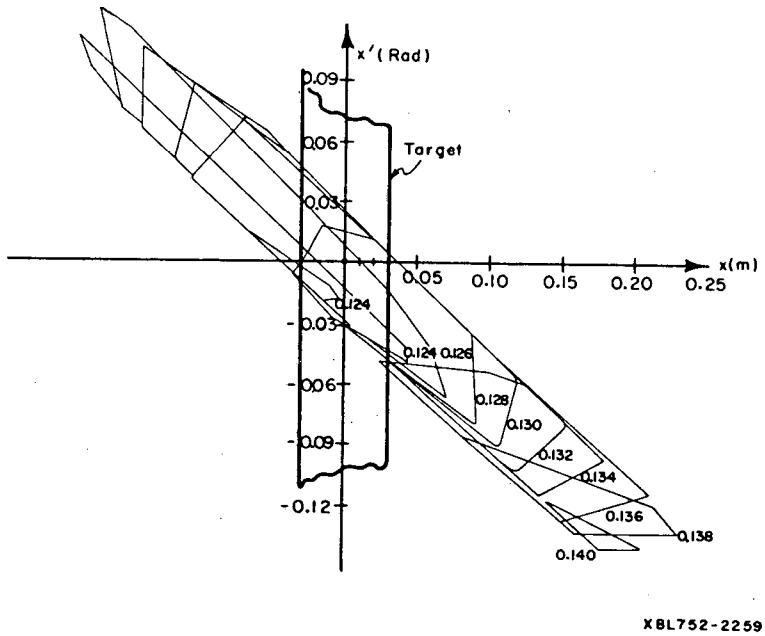

Fig. 5-13. The horizontal phase space acceptance of the π-μ channel of example 2 plotted as a function of momentum.

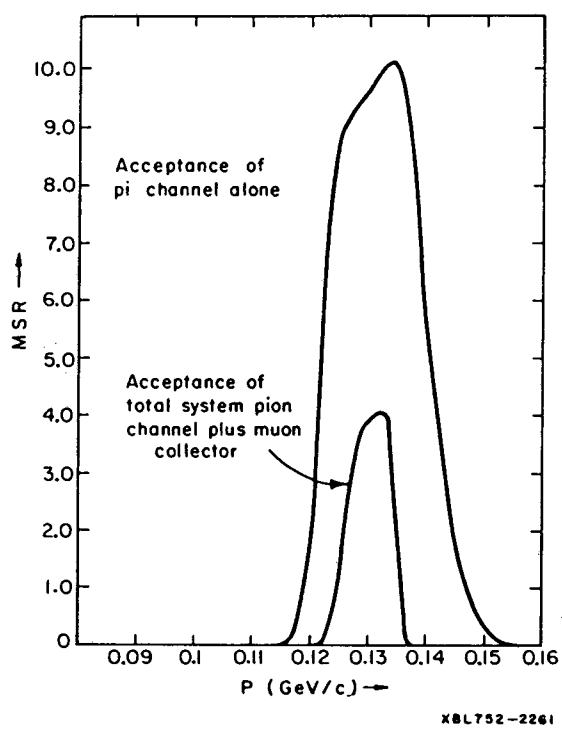

Fig. 5-14. The momentum acceptance as determined by the channel acceptance and production target for example 2.

```
6/18/74
1.
ESCAR LATTICE NO-2   4-4-74
0
13 2
15 5 BLK 1.
15 1 CM 1
15 2 MP 1
15 8 M 1
15 9 KG 1 UNITB
15 11 DEV 1.
16 15 .7 8 7 CM QUAD APERTURE
24 0
22 3.274 0 0 0 0 1
$  ESCAR 5/23/74  BX=3.355289, EX=2 PI    BY=1.639863  EY=16 PI
$  DATA LOAD,RING1,BIGJOHN
$  15 KLM TJ , K=FAY NO.  L=PLANE, M=1 2 3 4 5 OR 6
16 214 11 $ SI(1,1)
15 234 22 $ SI(2,2)
16 316 11 $ VEC 1 POXTION X
16 336 12 $ VEC1 XP POSITION
16 415 11 $ SQRT(SI(1,1))= SMALL R11
16 435 22 $ SQRT(SI(2,2))=SMALL R22
1 1 3.334 1 5.096 0 0 5
12. 0015 TILTS
7. 056
17
13 2 START
3 3 LL
5 .6 12.5 10 Q1
3 .2 0
5 .6 -12.5 10 Q2
3 .7 A
5 .6 -15.57 10 Q3
3 .2 0
5 .6 19.41 10 Q4
3 .86 L
16 22 2 $ RECTANGULAR MAGNETS
16 21 2 $ INPUT L AND ALPHA
4 .95 15 0
3 .43 S
4 .95 15 0
3 .43 S
4 .95 15 0
3 .86 L
4 .95 15 0
3 .43 S
4 .95 15 0
3 .43 S
4 .95 15 0
3 .86 L
5 .6 19.41 10 Q4
3 .2 0
5 .6 -15.57 10 Q3
3 .7 8
5 .6 -12.5 10 Q2
3 .2 0
5 .6 12.5 10 Q1
3 3 LL
13 1
13 4
25 QUART -1 8 QUART
6 0 1 $ UPDATE BEAM
9 4
25 QUART 8 0 USE13
13 1
9 0
25 FULLT -1 8 FULLT
25 FULL2 -1 8 FULL2 $ INITALIZE MATRIX 3
25 FULL4 -1 0 FULL4 $ INITALIZE MATRIX 4
13 2 END
SENTINEL
ADD SECOND ORDER AND SEXTUPOLE TO USE25 1-IST ORDER MATRIX INTYPE=2
2
0 START END

9 1 REP20
25 FULLT 0 0 USE25
18 .1 10 1 SEXT
13 1
9 0
25 FULL4 -1 0 ESCAR
SENTINEL
RUN ESCAR + SEXTUPOLE EXCITER FOR 99 REVOLUTIONS
1
22 1 0 0 0 0 0 2
2
0 SEXT
0 ESCAR
A USE25 2 FULL4 $ USE ESCAR MATRIX FULL4
A REP20  2 99  $  99 REVOLUTIONS I. E. REPEATES
A PLOT1 5 92.1  $  EACH LINE OF PLOT = 92.1 M

24 7 2 1 14 10 160 $ PHASE PLOT VEC 2
24 7 3 -2 1.2 -7 4 $ PHASE PLOT VEC 3
SENTINEL
SENTINEL
```

Fig. 5-15. Example 3 input data for study of the ESCAR ring lattice.

```
DATE=6/18/74                                                                                                                    CASE NUMBER   1-  0-F

ESCAR LATTICE NO-2   4-4-74
    1(T01  )    13.000000     2.000000
    3(UNIT1 )       15.0          5.0        BLK            1.0
    7(UNIT2 )       15.0          1.0        CM             1.0
   11(UNIT3 )       15.0          2.0        MR             1.0
   15(UNIT4 )       15.0          5.0        M              1.0
   19(UNIT5 )       15.0          0.0        KG             1.0
   23(UNIT6 )       15.0         11.0        GEV            1.0
   27(D41   )    16.000000    16.000000      .700000
   30(PLOT1 )    24.000000     0.000000    -0.000000    -0.000000    -0.000000    -0.000000
   37(VEC1  )    22.000000     1.000000
                 22.000000     3.274000     0.000000     0.000000     0.000000     0.000000     1.000000    -0.000000
   39(DA2   )    16.000000   214.000000    11.000000
   42(DA3   )    16.000000   234.000000    22.000000
   45(DA4   )    16.000000   316.000000    11.000000
   48(DA5   )    16.000000   336.000000    12.000000
   51(DA6   )    16.000000   415.000000    11.000000
   54(DA7   )    16.000000   435.000000    22.000000
   57(BEAM1 )     1.000000     1.000000     3.334000     1.000000     5.096000     0.000000     0.000000     5.000000
   60(TILTS )    12.000000     0.000000     0.000000     0.000000     0.000000     0.000000     0.000000     0.000000
                               0.000000     0.000000     0.000000     0.000000     0.000000     0.000000     0.000000     0.000000
   81(AXIS1 )     7.000000     0.000000     0.000000     0.000000     0.000000     0.000000     0.000000
   88(SSC1  )    17.000000    -0.000000    -0.000000    -0.000000
   92(START )    13.000000     2.000000
   94(LL    )     3.000000     3.000000
   96(Q1    )     5.000000      .600000    12.500000    10.000000
  100(O     )     3.000000      .200000
  102(Q2    )     5.000000      .600000   -12.500000    10.000000
  105(A     )     3.000000      .700000
  108(Q3    )     5.000000      .600000   -15.570000    10.000000
  112(O     )     3.000000      .200000
  114(Q4    )     5.000000      .600000    19.410000    10.000000
  118(L     )     3.000000      .860000
  120(DA8   )    16.000000    22.000000     2.000000
  123(DA9   )    16.000000    21.000000     2.000000
  126(PM1   )     4.000000      .950000    15.000000     0.000000
  130(S     )     3.000000      .430000
  132(PM2   )     4.000000      .950000    15.000000     0.000000
  136(S     )     3.000000      .430000
  138(PM3   )     4.000000      .950000    15.000000     0.000000
  142(L     )     3.000000      .860000
  144(PM4   )     4.000000      .950000    15.000000     0.000000
  148(S     )     3.000000      .430000
  150(PM5   )     4.000000      .950000    15.000000     0.000000
  154(S     )     3.000000      .430000
  156(PM6   )     4.000000      .950000    15.000000     0.000000
  160(L     )     3.000000      .860000
  162(Q4    )     5.000000      .600000    19.410000    10.000000
  165(O     )     3.000000      .200000
  168(Q3    )     5.000000      .600000   -15.570000    10.000000
  172(A     )     3.000000      .700000
  174(Q2    )     5.000000      .600000   -12.500000    10.000000
  178(O     )     3.000000      .200000
  180(Q1    )     5.000000      .600000    12.500000    10.000000
  184(LL    )     3.000000     3.000000
  186(T02   )    13.000000     1.000000
  188(T03   )    13.000000     4.000000
  190(CUART )       25.0       QUART         -1.0         0.0
  194(SLTT1 )     0.000000     0.000000     1.000000    -0.000000

  198(PEP1  )     9.000000     4.000000
  200(USE13 )       25.0       QUART          0.0         0.0
  204(T04   )    13.000000     1.000000
  206(PEP2  )     9.000000     0.000000
  209(FULLT )       25.0       FULLT         -1.0         0.0
  212(FULL2 )       25.0       FULL2         -1.0         0.0
  216(FULL4 )       25.0       FULL4         -1.0         0.0
  220(END   )    13.000000     2.000000

UNIT()=  2.998E-04  1.000E-03  2.998E-04  1.000E-03  2.998E-04  1.000E-02  1.000E+00  2.998E-02  1.000E+00  5.108E-04  1.000E+00
PAR  16.0   ( 16.0)          .70000
PLOTS 24.0          0   -0.0000 CM    -0.0000 CM    -0.0000 M      -0.0000    -0.0000
                                                                  ..X(CM )..  .XP(MR )..  ..Y(CM )..  .YP(MR )..  ..S(CM )..  .OP(PC )..  ....COM
                                                VECTOR  1(A)   3.274E+00  0.          0.          0.          0.          1.000E+00  -0.0000
PAR  16.0   (214.0)         11.00000
PAR  16.0   (234.0)         22.00000
PAR  16.0   (316.0)         11.00000
PAR  16.0   (336.0)         12.00000
PAR  16.0   (415.0)         11.00000
PAR  16.0   (435.0)         22.00000
BEAM  1.000000    5.00000 GEV                                                    A-TABLE NO.= 1     LENGTH=    0.000 M    BEAM1 - 57
AXIS SHIFT  7.000000   0.000    0.000    0.000    0.000    0.000                A-TABLE NO.= 1     LENGTH=    0.000 M    AXIS1 - 81
2ND ORDER17.0     MOM  1.0 0.0 3.0
DRIFT 3.0     3.000 M                                                           A-TABLE NO.= 2     LENGTH=    3.000 M    LL    - 94
QUAD  5.00     .600 M    12.5000 KG  10.00 CM   (   2.33 M  )                  A-TABLE NO.= 3     LENGTH=    3.600 M    Q1    - 96
DRIFT 3.0      .200 M                                                           A-TABLE NO.= 4     LENGTH=    3.800 M    O     -100
QUAD  5.00     .600 M   -12.5000 KG  10.00 CM   (  -2.13 M  )                  A-TABLE NO.= 5     LENGTH=    4.400 M    Q2    -102
DRIFT 3.0      .700 M                                                           A-TABLE NO.= 6     LENGTH=    5.100 M    A     -106
QUAD  5.00     .600 M   -15.5700 KG  10.00 CM   (  -1.69 M  )                  A-TABLE NO.= 7     LENGTH=    5.700 M    Q3    -108
DRIFT 3.0      .200 M                                                           A-TABLE NO.= 8     LENGTH=    5.900 M    O     -112
QUAD  5.00     .600 M    19.4100 KG  10.00 CM   (   1.54 M  )                  A-TABLE NO.= 9     LENGTH=    6.500 M    Q4    -114
DRIFT 3.0      .860 M                                                           A-TABLE NO.=10     LENGTH=    7.360 M    L     -118
PAR  16.0   ( 22.0)         2.00000
PAR  16.0   ( 21.0)         2.00000
POBAT 4.0    7.500 0     0.00 KG                                               A-TABLE NO.=11     LENGTH=    8.310 M    BM1   -126
BEND  4.000    .950 M    45.951 KG     .0000    ( 15.0000 0)
             (RHO=    3.629 M    2ND=    0.000  RAD1=    0.000 M    RAD2=    0.000 M   )
```

Fig. 5-16. Second order output for the ESCAR ring.

(Fig. 16-continued)

```
ROPAT 4.0    7.500 D     0.00 KG
DRIFT 3.0     .470 M                                          A-TABLE NO.=12     LENGTH=    8.760 M    S     -130
ROPAT 4.0    7.500 D     0.00 KG                              A-TABLE NO.=13     LENGTH=    9.690 M    BM2   -132
BEND  4.000   .950 M    45.961 KG     .0000    ( 15.0000 D)
             (RHO=    3.629 M    2ND=   0.000  RAD1=   0.000 M    RAD2=   0.000 M   )
ROPAT 4.0    7.500 D     0.00 KG
DRIFT 3.0     .430 M                                          A-TABLE NO.=14     LENGTH=   10.120 M    S     -136
ROPAT 4.0    7.500 D     0.00 KG                              A-TABLE NO.=15     LENGTH=   11.070 M    BM3   -138
BEND  4.000   .950 M    45.961 KG     .0000    ( 15.0000 D)
             (RHO=    3.629 M    2ND=   0.000  RAD1=   0.000 M    RAD2=   0.000 M   )
ROPAT 4.0    7.500 D     0.00 KG
DRIFT 3.0     .460 M                                          A-TABLE NO.=16     LENGTH=   11.930 M    L     -142
ROPAT 4.0    7.500 D     0.00 KG                              A-TABLE NO.=17     LENGTH=   12.880 M    BM4   -144
BEND  4.000   .950 M    45.961 KG     .0000    ( 15.0000 D)
             (RHO=    3.629 M    2ND=   0.000  RAD1=   0.000 M    RAD2=   0.000 M   )
ROPAT 4.0    7.500 D     0.00 KG
DRIFT 3.0     .430 M                                          A-TABLE NO.=18     LENGTH=   13.310 M    S     -148
ROPAT 4.0    7.500 D     0.00 KG                              A-TABLE NO.=19     LENGTH=   14.260 M    BM5   -150
BEND  4.000   .950 M    45.961 KG     .0000    ( 15.0000 D)
             (RHO=    3.629 M    2ND=   0.000  RAD1=   0.000 M    RAD2=   0.000 M   )
ROPAT 4.0    7.500 D     0.00 KG
DRIFT 3.0     .430 M                                          A-TABLE NO.=20     LENGTH=   14.690 M    S     -154
ROPAT 4.0    7.500 D     0.00 KG                              A-TABLE NO.=21     LENGTH=   15.640 M    BM6   -156
BEND  4.000   .950 M    45.961 KG     .0000    ( 15.0000 D)


             (RHO=    3.629 M    2ND=   0.000  RAD1=   0.000 M    RAD2=   0.000 M   )
ROPAT 4.0    7.500 D     0.00 KG
DRIFT 3.0     .860 M                                          A-TABLE NO.=22     LENGTH=   16.500 M    L     -160
QUAD  5.00    .600 M    19.4110 KG  10.00 CM   (   1.54 M  )  A-TABLE NO.=23     LENGTH=   17.100 M    Q4    -162
DRIFT 3.0     .280 M                                          A-TABLE NO.=24     LENGTH=   17.300 M    O     -166
QUAD  5.00    .600 M   -15.5700 KG  10.00 CM   (  -1.69 M  )  A-TABLE NO.=25     LENGTH=   17.900 M    Q3    -168
DRIFT 3.0     .700 M                                          A-TABLE NO.=26     LENGTH=   18.600 M    A     -172
QUAD  5.00    .600 M   -12.5000 KG  10.00 CM   (  -2.13 M  )  A-TABLE NO.=27     LENGTH=   19.280 M    Q2    -174
DRIFT 3.0     .200 M                                          A-TABLE NO.=28     LENGTH=   19.400 M    O     -178
QUAD  5.00    .600 M    12.5000 KG  10.00 CM   (   2.33 M  )  A-TABLE NO.=29     LENGTH=   20.000 M    Q1    -180
DRIFT 3.0    3.000 M                                          A-TABLE NO.=30     LENGTH=   23.000 M    LL    -184
                                                                   -.007   1.001 CM
                                                                    .028   3.331 MR     -.001
                                                                   0.000   1.001 CM     0.000 0.000
                                                                   0.000   5.091 MR     0.000 0.000 -.001
                                                                   -.066   1.211 CM      .630  .554 0.000 0.000
                                                                   0.000   0.000 PC     0.000 0.000 0.000 0.000 0.000
                                                  ..X(CM )..  .XP(MR )..  ..Y(CM )..  .YP(MR )..  ..S(CM )..  .DP(PC )..  ....COM
                                       VECTOR  1(A)   3.269E+00  2.400E-02  0.          0.         -3.658E-01  1.000E+00 -0.0000
TRANSFORM 1

        3.4262E-01 -2.7747E-01  0.          0.          0.          2.9155E+00
        3.0754E+00  3.4262E-01  0.          0.          0.         -1.8048E+01
        0.          0.          3.8335E-01 -1.8146E-01  0.          0.
        0.          0.          4.7010E+00  3.8335E-01  0.          0.
        1.0049E+00 -2.9155E-01  0.          0.          1.0000E+00 -3.6556E+00
        0.          0.          0.          0.          0.          1.0000E+00
2ND-ORDER TRANSFORM

 1 11 -7.188E-03
 1 12 -2.274E-03   1 22  1.766E-04
 1 13  0.          1 23  0.          1 33  1.629E-04
 1 14  0.          1 24  0.          1 34 -2.073E-04   1 44 -7.536E-05
 1 15  0.          1 25  0.          1 35  0.          1 45  0.          1 55  0.
 1 16 -1.603E-02   1 26 -1.393E-02   1 36  0.          1 46  0.          1 56  0.          1 66  1.169E-01

 2 11 -2.764E-03
 2 12  6.773E-04   2 22  2.133E-03
 2 13  0.          2 23  0.          2 33  4.768E-03
 2 14  0.          2 24  0.          2 34  1.098E-03   2 44  7.851E-05
 2 15  0.          2 25  0.          2 35  0.          2 45  0.          2 55  0.
 2 16 -4.415E-02   2 26 -6.665E-02   2 36  0.          2 46  0.          2 56  0.          2 66  2.292E-01

 3 11  0.
 3 12  0.          3 22  0.
 3 13  2.430E-03   3 23  1.021E-03   3 33  0.
 3 14 -2.058E-04   3 24  4.519E-05   3 34  0.          3 44  0.
 3 15  0.          3 25  0.          3 35  0.          3 45  0.          3 55  0.
 3 16  0.          3 26  0.          3 36 -8.136E-02   3 46 -2.040E-02   3 56  0.          3 66  0.

 4 11  0.
 4 12  0.          4 22  0.
 4 13 -6.037E-03   4 23  1.137E-03   4 33  0.
 4 14 -1.685E-03   4 24 -8.282E-04   4 34  0.          4 44  0.
 4 15  0.          4 25  0.          4 35  0.          4 45  0.          4 55  0.
 4 16  0.          4 26  0.          4 36 -2.261E-01   4 46 -6.795E-02   4 56  0.          4 66  0.

 5 11 -9.379E-03
 5 12 -3.544E-03   5 22 -6.357E-04
 5 13  0.          5 23  0.          5 33 -1.623E-02
 5 14  0.          5 24  0.          5 34 -7.142E-03   5 44 -1.294E-03
 5 15  0.          5 25  0.          5 35  0.          5 45  0.          5 55  0.
```

(Fig. 16-continued)

```
  5 16  3.473E-02   5 25 -9.978E-03   5 36  0.          5 46  0.          5 56  0.          5 66 -1.088E-01

  6 11  0.
  6 12  0.          6 22  0.
  6 13  0.          6 23  0.          6 33  0.
  6 14  0.          6 24  0.          6 34  0.          6 44  0.
  6 15  0.          6 25  0.          6 35  0.          6 45  0.          6 55  0.
  6 16  0.          6 26  0.          6 36  0.          6 46  0.          6 56  0.          6 66  0.
TSND  25.0   QUART    -1        0                                    A-TABLE NO.=31     LENGTH=   23.000 M    QUART -190
SLIT  6.0     0  1.0000                                              A-TABLE NO.=31     LENGTH=   23.000 M    SLIT1 -194
TSND  25.0   QUART     0        0                                    A-TABLE NO.=31     LENGTH=   46.000 M    USE13 -200
                                                              -.017   1.001 CM
                                                               .017   3.332 MR     .001
                                                              0.000   1.001 CM    0.000 0.000
                                                              0.000   5.093 MR    0.000 0.000  .001
                                                              -.145   2.715 CM     .383  .922 0.000 0.000
                                                              0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
                                          ..X(CM )..  .XP(MR )..  ..Y(CM )..  .YP(MR )..  ..S(CM )..  .OP(PC )..  ....COM
                                VECTOR  1(A)  3.261E+00  1.937E-02  0.          0.         -7.413E-01  1.000E+00 -0.0000
TSND  25.0   QUART     0        0                                    A-TABLE NO.=32     LENGTH=   69.000 M    USE13 -200
                                                              -.019   1.000 CM
                                                              -.019   3.333 MR    -.001
                                                              0.000   1.000 CM    0.000 0.000
                                                              0.000   5.095 MR    0.000 0.000 -.001
                                                              -.232   2.143 CM    -.194  .978 0.000 0.000
                                                              0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
                                          ..X(CM )..  .XP(MR )..  ..Y(CM )..  .YP(MR )..  ..S(CM )..  .OP(PC )..  ....COM
                                VECTOR  1(A)  3.259E+00 -9.947E-03  0.          0.         -1.124E+00  1.000E+00 -0.0000
TSND  25.0   QUART     0        0                                    A-TABLE NO.=33     LENGTH=   92.000 M    USE13 -200
                                                              -.009   1.001 CM
                                                              -.036   3.330 MR    -.000
                                                              0.000   1.001 CM    0.000 0.000
                                                              0.000   5.090 MR    0.000 0.000 -.000
                                                              -.313   1.557 CM    -.699  .699 0.000 0.000
                                                              0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
                                          ..X(CM )..  .XP(MR )..  ..Y(CM )..  .YP(MR )..  ..S(CM )..  .OP(PC )..  ....COM
                                VECTOR  1(A)  3.266E+00 -2.599E-02  0.          0.         -1.503E+00  1.000E+00 -0.0000
TSND  25.0   QUART     0        0                                    A-TABLE NO.=34     LENGTH=  115.000 M    USE13 -200
                                                              -.000   1.000 CM
                                                              -.013   3.333 MR     .001
                                                              0.000   1.000 CM    0.000 0.000
                                                              0.000   5.095 MR    0.000 0.000  .001
                                                              -.381    .512 CM    -.811  .162 0.000 0.000
                                                              0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
                                          ..X(CM )..  .XP(MR )..  ..Y(CM )..  .YP(MR )..  ..S(CM )..  .OP(PC )..  ....COM
                                VECTOR  1(A)  3.273E+00 -9.935E-03  0.          0.         -1.872E+00  1.000E+00 -0.0000
TSND  25.0   FULLT    -1        0                                    A-TABLE NO.=35     LENGTH=  115.000 M    FULLT -208
TSND  25.0   FULL2    -1        0                                    A-TABLE NO.=35     LENGTH=  115.000 M    FULL2 -212
TSND  25.0   FULL4    -1        0                                    A-TABLE NO.=35     LENGTH=  115.000 M    FULL4 -216
LENGTH 115.000M
```

J	TYPE.III	L	APH	APV	H-BEAM	V-BEAM	H-CENT	V-CENT	HRAY1	VRAY1		
1	7.081	0.0000			1.0000	1.0000	0.	0.	3.274	0.	1	7.081-AXIS1
2	3.094	3.9000			1.414	1.827	0.	0.	3.274	0.	2	3.094-LL
3	5.096	3.6900	7.000	7.000	1.370	2.353	0.	0.	2.842	0.	3	5.096-01
4	3.100	3.8000			1.294	2.626	0.	0.	2.561	0.	4	3.100-O
5	5.102	4.4000	7.000	7.000	1.250	3.066	0.	0.	2.031	0.	5	5.102-02
6	3.106	5.1000			1.418	3.113	0.	0.	1.753	0.	6	3.106-A
7	5.108	5.7000	7.000	7.000	1.831	2.646	0.	0.	1.605	0.	7	5.108-03
8	3.112	5.9000			2.063	2.338	0.	0.	1.919	0.	8	3.112-O
9	5.114	6.5000	7.000	7.000	2.296	1.826	0.	0.	1.851	0.	9	5.114-04
10	3.116	7.3600			1.947	1.707	0.	0.	1.170	0.	10	3.116-L

(Fig. 16-continued)

11	4.126	8.3100			1.579	1.563	-2.2503E-03	0.	.5500	0.	11	4.126-BM1
12	3.130	8.7400			1.418	1.493	-2.6423E-03	0.	.3228	0.	12	3.130-S
13	4.132	9.6900			1.096	1.342	-4.9567E-03	0.	-4.9938E-02	0.	13	4.132-BM2
14	3.136	10.1200			.9709	1.283	-5.6426E-03	0.	-.1640	0.	14	3.136-S
15	4.138	11.0700			.7891	1.194	-7.8702E-03	0.	-.2894	0.	15	4.138-BM3
16	3.142	11.9300			.7877	1.193	-9.7441E-03	0.	-.2910	0.	16	3.142-L
17	4.144	12.8800			.9698	1.281	-1.1655E-02	0.	-.1691	0.	17	4.144-BM4
18	3.148	13.3100			1.095	1.340	-1.2879E-02	0.	-5.6720E-02	0.	18	3.148-S
19	4.150	14.2600			1.417	1.491	-1.4774E-02	0.	.3124	0.	19	4.150-BM5
20	3.154	14.6900			1.578	1.561	-1.6334E-02	0.	.5381	0.	20	3.154-S
21	4.156	15.6400			1.946	1.706	-1.8442E-02	0.	1.155	0.	21	4.156-BM6
22	3.160	16.5000			2.295	1.825	-2.2497E-02	0.	1.832	0.	22	3.160-L
23	5.162	17.1000	7.000	7.000	2.062	2.329	-2.0582E-02	0.	1.902	0.	23	5.162-Q4
24	3.166	17.3000			1.830	2.645	-1.8407E-02	0.	1.789	0.	24	3.166-Q
25	5.168	17.9000	7.000	7.000	1.418	3.112	-1.4691E-02	0.	1.741	0.	25	5.168-Q3
26	3.172	18.6000			1.250	3.065	-1.3393E-02	0.	2.021	0.	26	3.172-A
27	5.174	19.2000	7.000	7.000	1.295	2.626	-1.4076E-02	0.	2.550	0.	27	5.174-Q2
28	3.178	19.4000			1.370	2.352	-1.4913E-02	0.	2.830	0.	28	3.178-Q
29	5.180	20.0000	7.000	7.000	1.415	1.827	-1.5346E-02	0.	3.262	0.	29	5.180-Q1
30	3.184	23.0000			1.001	1.001	-7.0194E-03	0.	3.269	0.	30	3.184-LL
31	25.200	46.0000			1.001	1.001	-1.7415E-02	0.	3.261	0.	31	25.200-USE13
32	25.200	69.0000			1.000	1.000	-1.8342E-02	0.	3.259	0.	32	25.200-USE13
33	25.200	92.0000			1.001	1.001	-8.6380E-03	0.	3.266	0.	33	25.200-USE13
34	25.200	115.0000			1.000	1.000	-3.1870E-04	0.	3.273	0.	34	25.200-USE13

J	TYPE.III	L	HRAY2	VRAY2	HRAY3	VRAY3	HRAY4	VRAY4	HRAY5	VRAY5	HRAY6	VRAY6
1	7.081	0.0000	1.000	11.12	3.274	0.	2.9979E-04	3.3340E-03	0.	0.	0.	0.
2	3.094	3.9000	2.000	11.12	3.274	0.	4.2401E-04	3.3340E-03	0.	0.	0.	0.
3	5.096	3.6000	1.876	20.44	2.842	-14.07	4.1062E-04	4.5209E-03	0.	0.	0.	0.
4	3.100	3.8000	1.675	20.44	2.561	-14.07	3.8805E-04	4.5209E-03	0.	0.	0.	0.
5	5.102	4.4000	1.563	12.04	2.031	-3.970	3.7495E-04	3.4704E-03	0.	0.	0.	0.
6	3.106	5.1000	2.011	12.04	1.753	-3.970	4.2517E-04	3.4704E-03	0.	0.	0.	0.
7	5.108	5.7000	3.353	137.3	1.605	5.725	5.4899E-04	1.1719E-02	0.	0.	0.	0.
8	3.112	5.9000	4.256	137.3	1.919	5.725	6.1858E-04	1.1719E-02	0.	0.	0.	0.
9	5.114	6.5000	5.273	18.98	1.851	-7.918	6.8844E-04	4.3567E-03	0.	0.	0.	0.
10	3.118	7.3000	3.791	18.98	1.170	-7.918	5.8374E-04	4.3567E-03	0.	0.	0.	0.
11	4.126	8.3100	2.494	18.98	.5500	-5.245	4.7340E-04	4.3567E-03	0.	0.	0.	0.
12	3.130	8.7400	2.011	18.98	.3228	-5.285	4.2515E-04	4.3567E-03	0.	0.	0.	0.
13	4.132	9.6900	1.201	18.98	-4.9930E-02	-2.652	3.2861E-04	4.3569E-03	0.	0.	0.	0.
14	3.136	10.1200	.9425	18.98	-.1640	-2.652	2.9106E-04	4.3568E-03	0.	0.	0.	0.
15	4.138	11.0700	.6211	18.98	-.2894	-1.8871E-02	2.3629E-04	4.3568E-03	0.	0.	0.	0.
16	3.142	11.9300	.6204	18.98	-.2910	-1.8871E-02	2.3616E-04	4.3568E-03	0.	0.	0.	0.
17	4.144	12.8800	.9404	18.98	-.1691	2.614	2.9075E-04	4.3568E-03	0.	0.	0.	0.
18	3.148	13.3100	1.199	18.98	-5.6720E-02	2.614	3.2875E-04	4.3568E-03	0.	0.	0.	0.
19	4.150	14.2600	2.007	18.98	.3124	5.247	4.2472E-04	4.3568E-03	0.	0.	0.	0.
20	3.154	14.6900	2.449	18.98	.5381	5.247	4.7296E-04	4.3568E-03	0.	0.	0.	0.
21	4.156	15.6400	3.785	18.98	1.155	7.880	5.6327E-04	4.3569E-03	0.	0.	0.	0.
22	3.160	16.5000	5.266	18.98	1.832	7.880	6.8797E-04	4.3569E-03	0.	0.	0.	0.
23	5.162	17.1000	4.251	137.1	1.902	-5.633	6.1812E-04	1.1709E-02	0.	0.	0.	0.
24	3.166	17.3000	3.349	137.1	1.789	-5.633	5.4667E-04	1.1789E-02	0.	0.	0.	0.
25	5.168	17.9000	2.009	12.02	1.741	3.988	4.2499E-04	3.4667E-03	0.	0.	0.	0.
26	3.172	18.6000	1.563	12.02	2.021	3.988	3.7481E-04	3.4667E-03	0.	0.	0.	0.
27	5.174	19.2000	1.876	20.49	2.550	14.04	3.8813E-04	4.5264E-03	0.	0.	0.	0.
28	3.178	19.4000	1.877	20.49	2.830	14.04	4.1073E-04	4.5264E-03	0.	0.	0.	0.
29	5.180	20.0000	2.002	11.09	3.262	2.4004E-02	4.2423E-04	3.3306E-03	0.	0.	0.	0.
30	3.184	23.0000	1.002	11.09	3.269	2.4004E-02	3.0015E-04	3.3306E-03	0.	0.	0.	0.
31	25.200	46.0000	1.001	11.10	3.261	1.8369E-02	3.0003E-04	3.3320E-03	0.	0.	0.	0.
32	25.200	69.0000	1.000	11.11	3.259	-9.9475E-03	2.9997E-04	3.3334E-03	0.	0.	0.	0.
33	25.200	92.0000	1.003	11.09	3.266	-2.5981E-02	3.0019E-04	3.3300E-03	0.	0.	0.	0.
34	25.200	115.0000	1.000	11.11	3.273	-9.9345E-03	2.9996E-04	3.3334E-03	0.	0.	0.	0.

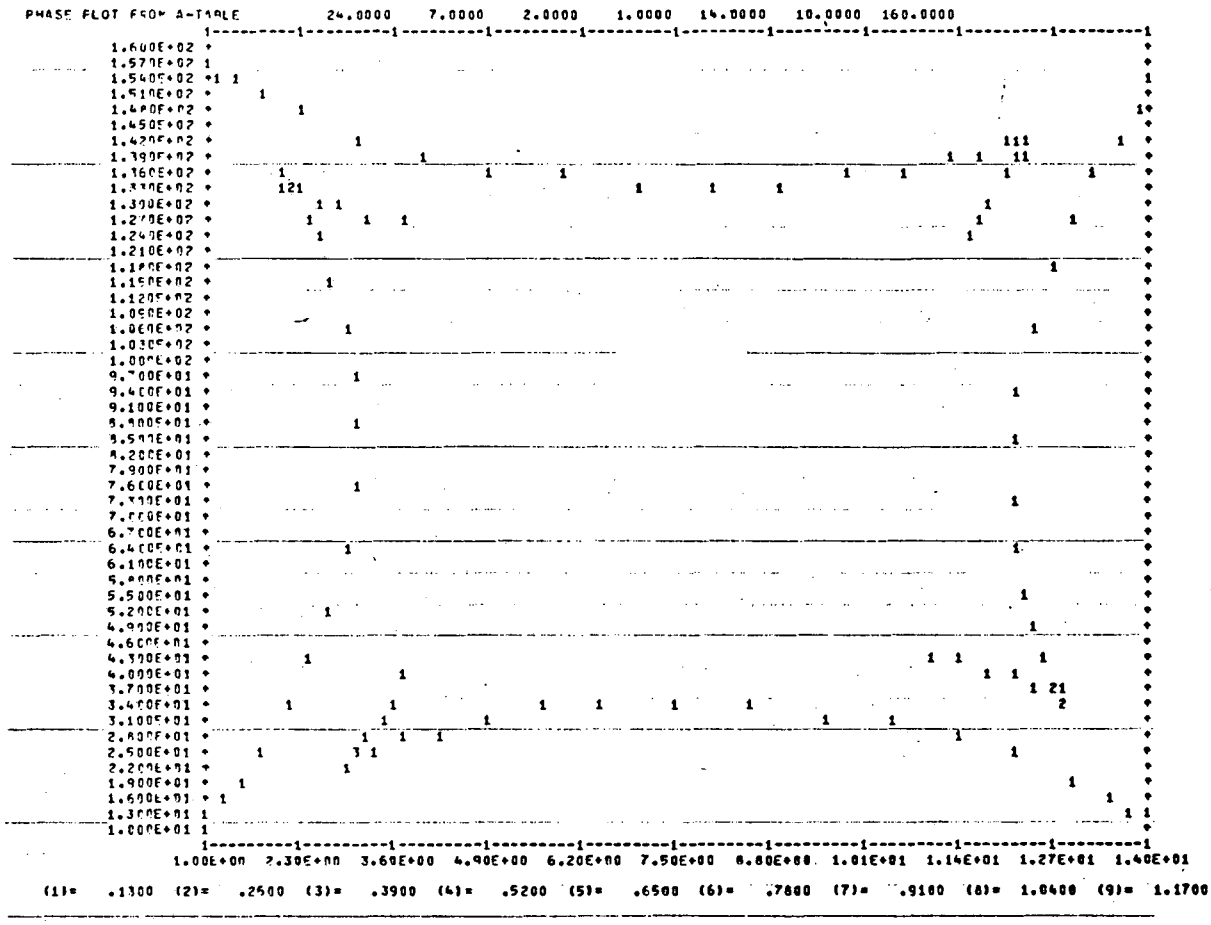

Fig. 5-17. Plot of the horizontal beam projects on the x and xp axis showing effect of the sextupole exciter.

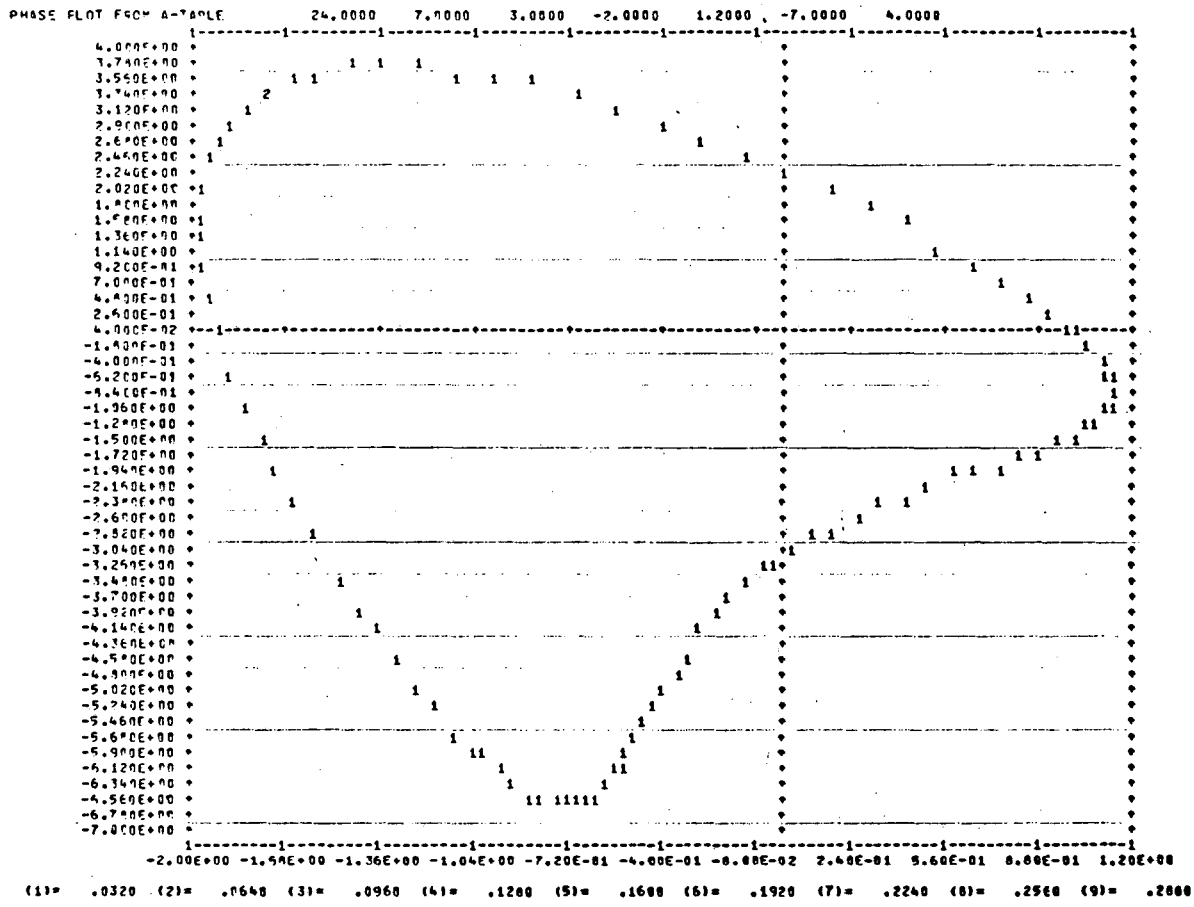

Fig. 5-18. Phase space trace of vector 1 for 99 revolutions in ESCAR.

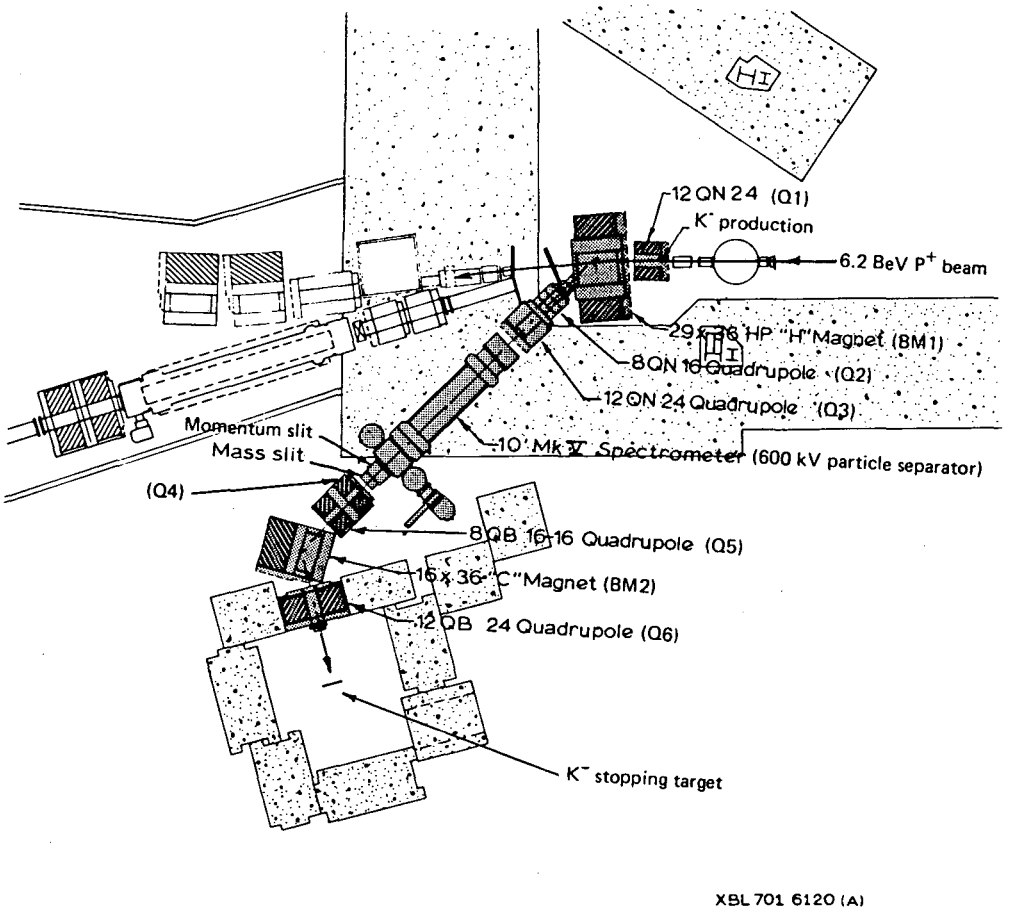

Fig. 5-19. K^- beam layout for example 4.

```
LBL K BEAM WITH SEPARATORS
0                                          $ OPTION 0 DATA INPUT
15 3 0 1                                   $ UNIT CHANGES TO FOLLOW
15 1 IN 2.54                               $ X IN INCHES
15 8 IN .0254                              $ DRIFT LENGTH IN INCHES
15 11 MEV/C .001                           $ MOMENTUM IN MEV/C
1 .2 150. .1 17.5 0 0 500                  $ BEAM OF KAONS
22 OR5 1.                                  $ 1 PERCENT MOMENTUM VECTOR
22 OR6 .96346                              $ PIONS OF BETA 0.96346
22 .2 0 .1 OR3 .96346
22 0 150 0 17.5 0 0 .96346
22 -.2 0 -.1 0 0 0 .96346
22 0 -150 0 -17.5 0 0 .96346
13 2                                       $ SUPPRESS BEAM OUTPUT
17.                                        $ START SECOND ORDER CALCULATIONS
24 OR4 1 6                                 $ BEAM LINE PLOT
3 2.63                                     $ DRIFT LENGTH OF 2.63 INCHES
16 16 0.8                                  $ USE .8 OF QUAD APERTURES
5 28.74 10.67 6
3 8.73
16 4 6                                     $ HORIZONTAL BENDING APERUTRE
16 5 4.0625                                $ VERTICAL BENDING APERUTRE
2 5
4 47.5 11.447 0
2 40
3 17.77
5 20 -2.243 4
3 7
5.00 30.0 2.382 6.
3 27.05
23 -120 .56 6 2 0.7114                     $ SEPARATOR K BETA .7114
3 22.55
6 2 1 6                                    $ MASS SLIT
3 12.18
-10 2 1 0 .001                             $ LOCATION OF HOR WAIST
3 .96
6 2 6  .1875                               $ MOMENTUM SLIT
13 1                                       $ OUTPUT BEAM AND VECTORS HERE
13 42.                                     $ MATRIX OUTPUT HERE
3 7.2
-10 4 3 0 .001                             $ VERTICAL WAIST
13 6                                       $ DO POLYGON CALCULATION
3 6.06
6 4 3 1
5 20 3.88 4
3 4
5 20 -3.331 4
3 13.33
2 30
3 12.33
5 30 5.368 6
3 15
3 27
6 5 1.5 1.5
13 1
13 42
24 1234                                    $ PLOT BEAM PHASE SPACE HERE
SENTINEL                                   $ END DATA FOR K BEAM
```

Fig. 5-20. The above beam data example is for a bevatron K-beam which has previously been solved. During this run the data will only process output, doing plots and calculation the first order separation of a pi-beam contamination from the K-beam. The pions are represented by the vectors while the kaons are represented by the beam card and will be separated from the pions by the separator based on their beta difference.

```
SLIT  6.0     2   6.0000 IN     .1875 IN                                    A-TABLE NO.-16     LENGTH=  345.110 IN   SLIT2 -172
                                                                   -.066   2.042 IN
                                                                   1.578  17.530 MR     .898
                                                                   0.000    .568 IN    0.000 0.000
                                                                   0.000  10.624 MR    0.000 0.000  .226
                                                                  -1.335   5.270 CM     .863  .939 0.000 0.000
                                                                   0.000   0.000 PC    0.000 0.000 0.000 0.000 0.000
                                                          ..X(IN )..  .XP(MR )..  ..Y(IN )..  .YP(MR )..  ..S(CM )..  .DP(PC )..  ....COM
                                        VECTOR  1(A)   1.239E+00  8.940E-01  0.          0.         -1.332E-01  1.000E+00 -0.0000
                                        VECTOR  2(B)   0.         0.          1.182E+00  1.236E+01  0.          0.          .9635
                                        VECTOR  3(C)  -8.166E-01  4.219E-01  1.100E+00  1.071E+01  3.182E-01  0.          .9635
                                        VECTOR  4(D)   8.166E-01 -4.219E-01  1.265E+00  1.400E+01 -3.182E-01  0.          .9635
                                        VECTOR  5(E)  -1.870E+00 -1.740E+01  1.202E+00  2.175E+00 -5.051E+00  0.          .9635
                                        VECTOR  6(F)   1.870E+00  1.740E+01  1.162E+00  2.254E+01  5.051E+00  0.          .9635
                                        VECTOR  7(G)   1.661E+00  2.210E+00 -8.271E-02 -1.647E+00  5.173E-02  2.000E+00 -0.0000
                                        VECTOR  8(H)   3.294E+00  1.366E+00  8.271E-02  1.647E+00 -5.847E-01  2.000E+00 -0.0000
                                        VECTOR  9(J)   4.348E+00  1.919E+01 -2.000E-02  1.018E+01  4.785E+00  2.000E+00 -0.0000
                                        VECTOR 10(K)   6.073E-01 -1.561E+01  2.000E-02 -1.018E+01 -5.318E+00  2.000E+00 -0.0000
TRANSFORM 1

      -8.1660E+00 -1.2469E-02  0.          0.          0.          1.2388E+00
       4.2193E+00 -1.1602E-01  0.          0.          0.          0.9401E-01
       0.          0.         -1.6542E+00  1.1429E-03  0.          0.
       0.          0.         -3.2949E+01 -5.8177E-01  0.          0.
       3.1820E+00 -3.3674E-02  0.          0.          1.0000E+00 -1.3323E-01
       0.          0.          0.          0.          0.          1.0000E+00
2ND-ORDER TRANSFORM

 1 11 -3.295E-01
 1 12 -8.658E-05   1 22 -1.910E-06
 1 13  0.          1 23  0.          1 33 -1.180E-01
 1 14  0.          1 24  0.          1 34 -5.412E-03   1 44 -6.295E-05
 1 15  0.          1 25  0.          1 35  0.          1 45  0.          1 55  0.
 1 16 -4.275E-02   1 26  1.460E-03   1 36  0.          1 46  0.          1 56  0.          1 66  2.715E-03

 2 11 -1.157E+00
 2 12  5.874E-03   2 22  6.087E-06
 2 13  0.          2 23  0.          2 33  8.805E+00
 2 14  0.          2 24  0.          2 34  4.058E-01   2 44  4.672E-03
 2 15  0.          2 25  0.          2 35  0.          2 45  0.          2 55  0.
 2 16 -7.778E-01   2 26 -1.335E-03   2 36  0.          2 46  0.          2 56  0.          2 66  9.531E-02

 3 11  0.
 3 12  0.          3 22  0.
 3 13 -5.907E+00   3 23 -8.315E-03   3 33  0.
 3 14 -1.359E-01   3 24 -1.920E-04   3 34  0.          3 44  0.
 3 15  0.          3 25  0.          3 35  0.          3 45  0.          3 55  0.
 3 16  0.          3 26  0.          3 36  1.459E+00   3 46  3.359E-02   3 56  0.          3 66  0.

 4 11  0.
 4 12  0.          4 22  0.
 4 13 -2.665E+01   4 23 -3.770E-02   4 33  0.
 4 14 -6.121E-01   4 24 -8.739E-04   4 34  0.          4 44  0.

 4 15  0.          4 25  0.          4 35  0.          4 45  0.          4 55  0.
 4 16  0.          4 26  0.          4 36  6.698E+00   4 46  1.510E-01   4 56  0.          4 66  0.

 5 11 -1.398E+00
 5 12  1.226E-04   5 22 -4.364E-05
 5 13  0.          5 23  0.          5 33 -2.084E+00
 5 14  0.          5 24  0.          5 34 -9.314E-02   5 44 -1.089E-03
 5 15  0.          5 25  0.          5 35  0.          5 45  0.          5 55  0.
 5 16  2.804E-01   5 26 -6.754E-04   5 36  0.          5 46  0.          5 56  0.          5 66 -2.105E-02

 6 11  0.
 6 12  0.          6 22  0.
 6 13  0.          6 23  0.          6 33  0.
 6 14  0.          6 24  0.          6 34  0.          6 44  0.
 6 15  0.          6 25  0.          6 35  0.          6 45  0.          6 55  0.
 6 16  0.          6 26  0.          6 36  0.          6 46  0.          6 56  0.          6 66  0.
2ND-ORDER T*SIGMA

 1 11 -3.295E-03
 1 12 -1.299E-03   1 22 -4.297E-02
 1 13  0.          1 23  0.          1 33 -2.949E-04
 1 14  0.          1 24  0.          1 34 -4.736E-03   1 44 -1.928E-02
 1 15  0.          1 25  0.          1 35  0.          1 45  0.          1 55  0.
 1 16 -0.          1 26  0.          1 36  0.          1 46  0.          1 56  0.          1 66  0.

 2 11 -1.157E-02
 2 12  8.812E-02   2 22  1.369E-01
 2 13  0.          2 23  0.          2 33  2.201E-02
 2 14  0.          2 24  0.          2 34  3.551E-01   2 44  1.431E+00
 2 15  0.          2 25  0.          2 35  0.          2 45  0.          2 55  0.
 2 16 -0.          2 26 -0.          2 36  0.          2 46  0.          2 56  0.          2 66  0.

 3 11  0.
 3 12  0.          3 22  0.
 3 13 -2.953E-02   3 23 -6.236E-02   3 33  0.
 3 14 -2.379E-01   3 24 -5.040E-01   3 34  0.          3 44  0.
 3 15  0.          3 25  0.          3 35  0.          3 45  0.          3 55  0.
 3 16  0.          3 26  0.          3 36  0.          3 46  0.          3 56  0.          3 66  0.

 4 11  0.
 4 12  0.          4 22  0.
 4 13 -1.333E-01   4 23 -2.827E-01   4 33  0.
 4 14 -1.071E+00   4 24 -2.294E+00   4 34  0.          4 44  0.
 4 15  0.          4 25  0.          4 35  0.          4 45  0.          4 55  0.
 4 16  0.          4 26  0.          4 36  0.          4 46  0.          4 56  0.          4 66  0.

 5 11 -1.398E-02
 5 12  1.839E-03   5 22 -9.819E-01
 5 13  0.          5 23  0.          5 33 -5.211E-03
 5 14  0.          5 24  0.          5 34 -8.150E-02   5 44 -3.335E-01
 5 15  0.          5 25  0.          5 35  0.          5 45  0.          5 55  0.
 5 16  0.          5 26 -0.          5 36  0.          5 46  0.          5 56  0.          5 66 -0.

 6 11  0.
 6 12  0.          6 22  0.
 6 13  0.          6 23  0.          6 33  0.
 6 14  0.          6 24  0.          6 34  0.          6 44  0.
 6 15  0.          6 25  0.          6 35  0.          6 45  0.          6 55  0.
 6 16  0.          6 26  0.          6 36  0.          6 46  0.          6 56  0.          6 66  0.
```

Fig. 5-21. 1st and 2nd order transformation matrix at end of K^- beam line of example 4. The significance of the several second order aberrations is made apparent by the 2ND-ORDER T*SIGMA output shown.

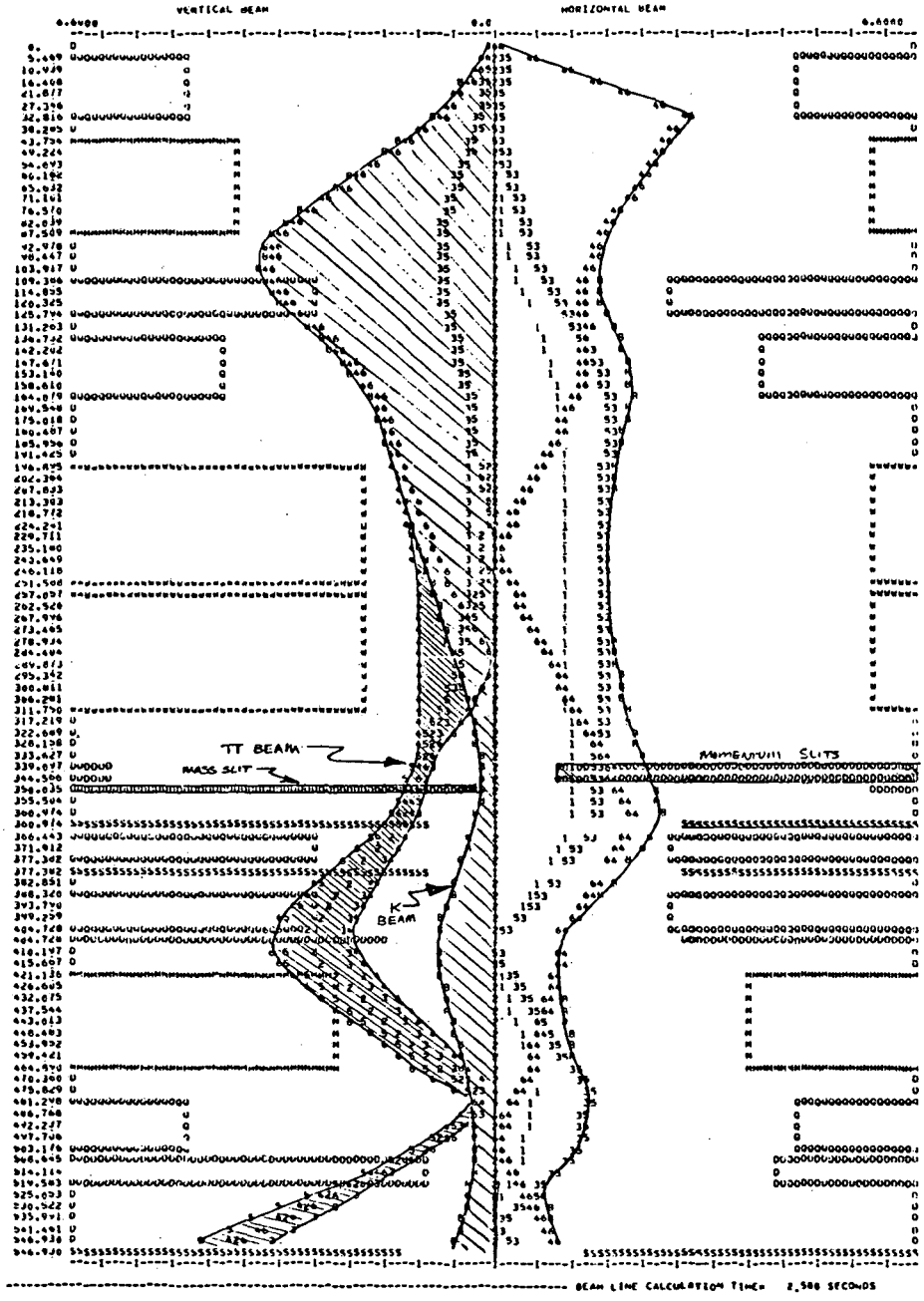

Fig. 5-22. First order beam plot of K^- beam, example 4.

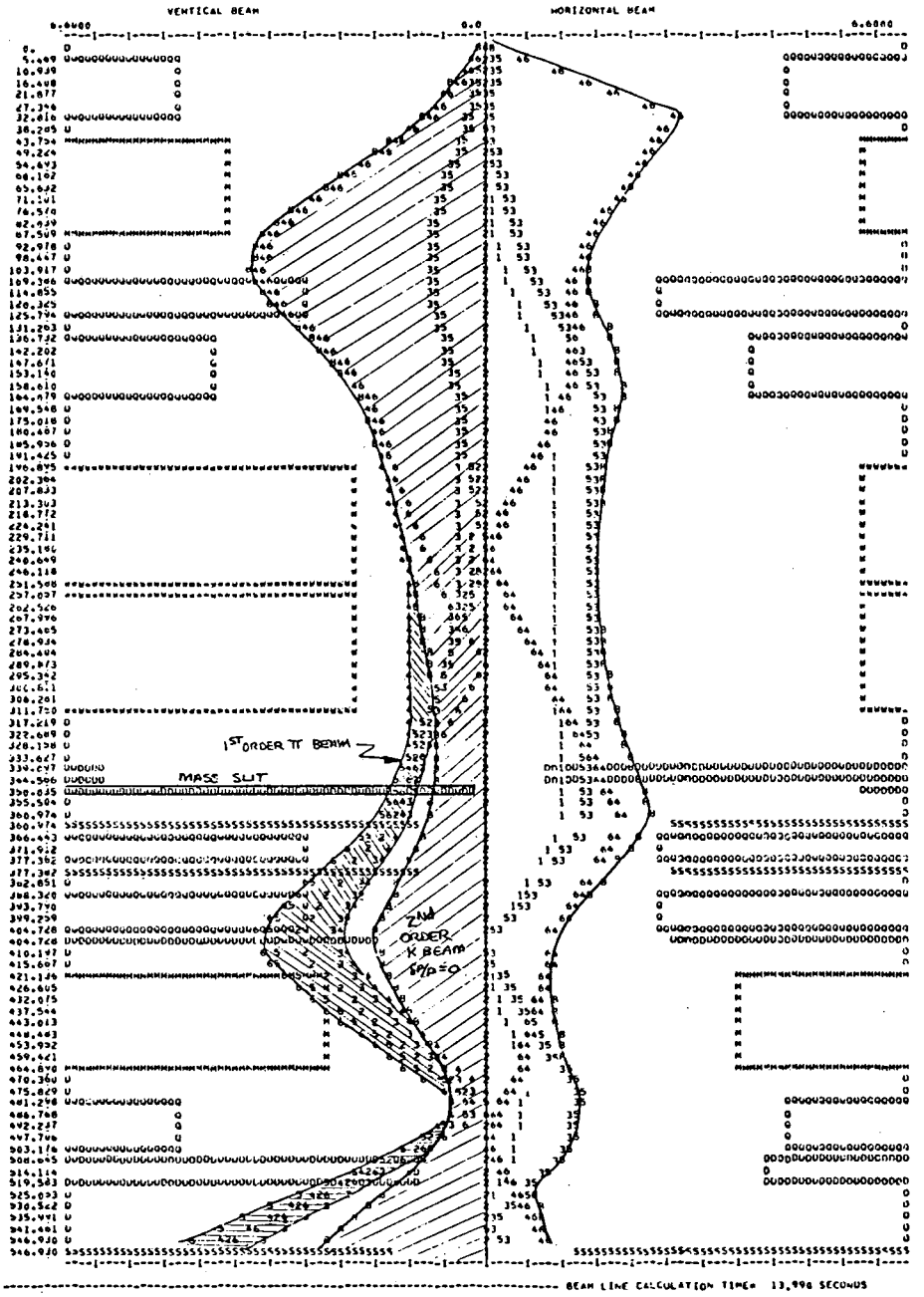

Fig. 5-23. Second order beam plot with no momentum spread.

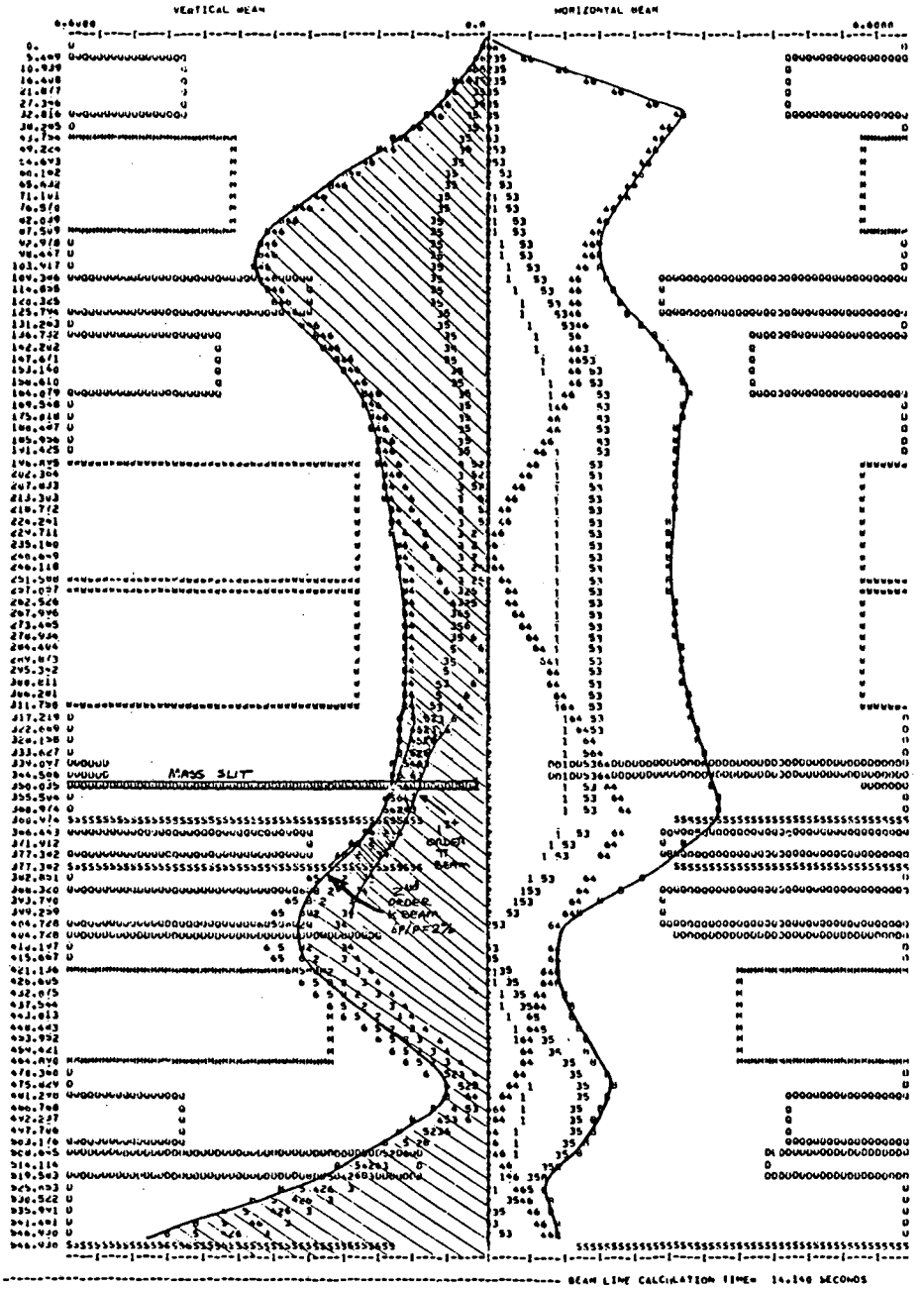

Fig. 5-24. Second order beam plot with 2% momentum spread. Notice the lack of vertical separation at the mass slit produced by the various second order effects and chromatic aberrations.

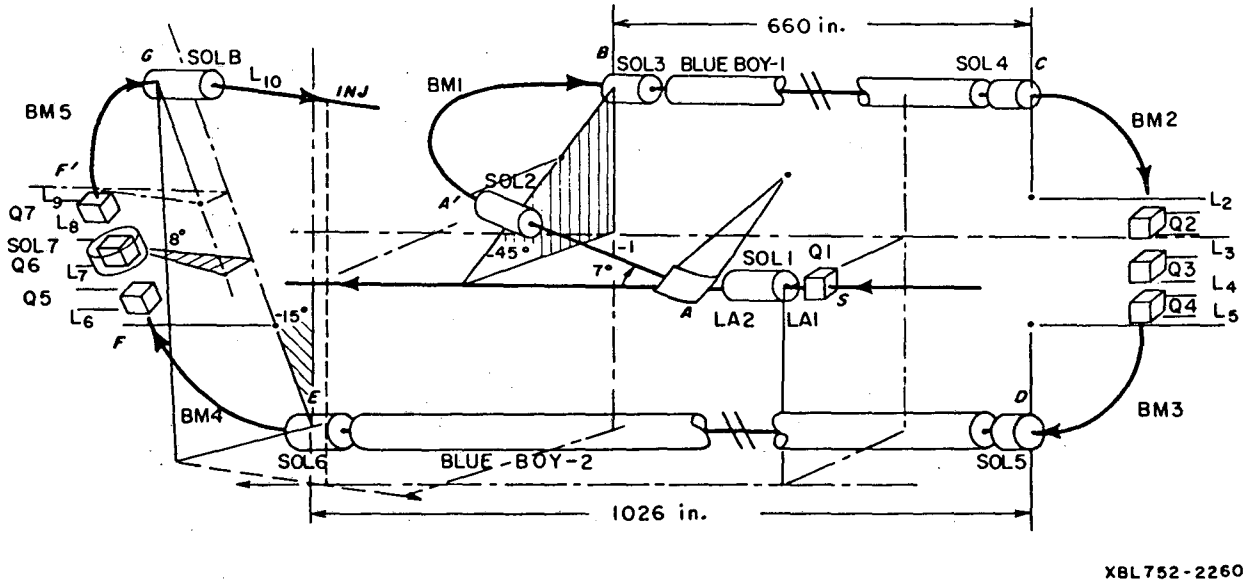

Fig. 5-25. ASTRON beam injection delay line layout, example 5.

```
ZERO GRADIENT TROBONE 6/16/72  ALL BM RADII=24 INCHES (160-51)
0
15.        6.        1.        1.
15.        1.        IN        2.54
15.        2.        MR        1.
15.        5.        IN        2.54
15.        6.        PC        1.
15.        8.        IN        .0254
15.        11.       MEV/C     .001
13 2
16 16 .8
13.        46.
22.        0.        0.        0.        0.        0.        1.
1.         1.176     10.542    1.176     10.542    0.        0.        6.4909
12.        -.421     0.        0.        0.        0.        -.421     0.
C.         0.        0.        0.        0.        0.        0.        0.
16.        3.        1.
-26.       12.       800.      100.      0.
19.        36.       .225
3.         4.5
20.        -45.
16.        4.        2.
16.        5.        2.
16.        21.       1.
4.         7.        -.07      0.
3.         52.5
19.        6.        .75
16.        21.       0.
22.        0.        0.        0.        0.        0.        1.
6 0 2 RC2ON
4.         36.23292  -.35517   0.
4.         36.23292  -.35517   0.
13 24 RC2OUT
16 4 4.5
16 5 4.5
20.        0.
19.        36.       -.25
13.        1.
9.         24.
6.         2.        4.        4.
19.        25.       .180
9.         0.
19.        24.       .180
20.        45.
22.        0.        0.        0.        0.        0.        1.        0.
6 0 2 RC2ON
4.         37.717    -.355     0.
3.         5.
5.         8.        -.204     4.
3.         7.
5.         4.        .375      4.
5.         4.        .375      4.
3.         7.
5.         8.        -.204     4.
3.         5.
4.         37.717    -.355     0.
13 24 RC2OUT
20.        0.
19.        36.       .45
13.        1.
9.         36.
6.         2.        4.        4.
19.        26.5      .255
9.         0.
19.        36.       -.2
20.        -15.
22.        0.        0.        0.        0.        0.        1.        0.
6 0 2 RC2ON
4.         37.717    -.355     0.
3.         5.
5.         8.        -.18      4.
3.         5.625
5.         4.        .35       4.
20.        -8.
5.         4.        .35       4.
3.         5.625
5.         8.        -.18      4.
3.         5.
4.         37.717    -.355     0.
13 24 RC2OUT
20.        0.
13.        1.
19.        24.       .75
3.         24.
6.         2.        1.        1.
13.        1.
13.        4.
24. 0. 6. 6. 12. 1. 6.
24.        0.        6.        6.        48.       1.        1.
24.        121334.   4.        100.      4.        4.
73.
```

Fig. 5-26. Transport data input of example 5.

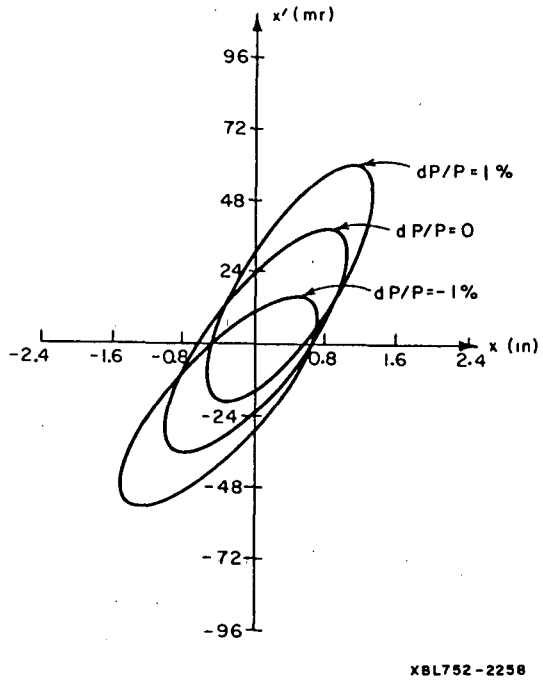

Fig. 5-27. Horizontal phase space at injection into ASTRON after passage through the delay line trombone.

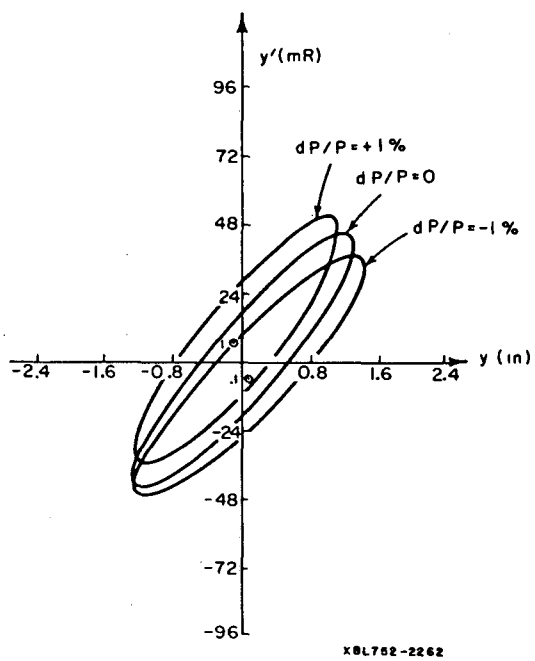

Fig. 5-28. Vertical phase space at injection into ASTRON after passage through the delay line trombone.

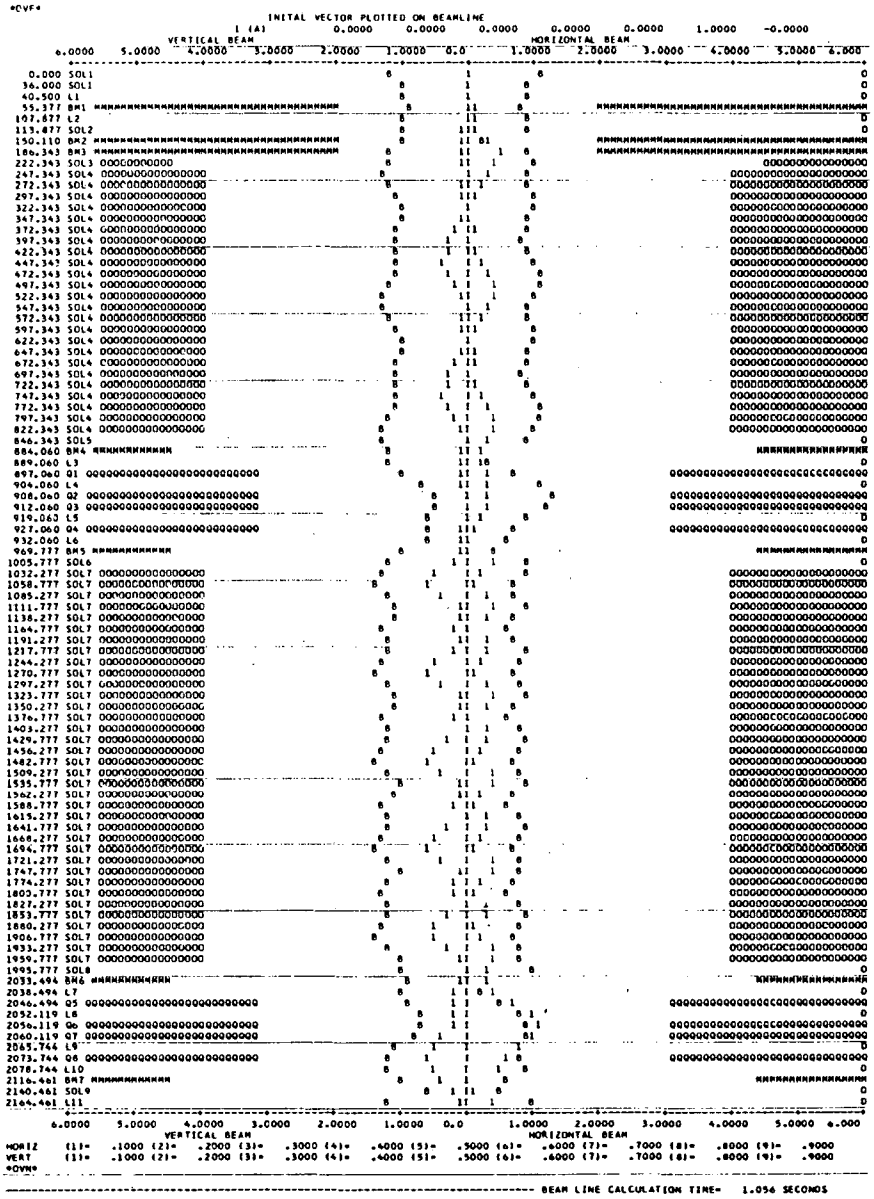

Fig. 5-29. Beam line profile for ASTRON injection Trombone, Note vector shows effect of a 1% momentum error.

```
6/18/74
1.
 FIRST HALF WITH Q1,Q3, AND Q4 MISALIGNMENT
 0
15.          5.          1.
15 1 IN 2.54
15 2 MP 1.0
15 5 IN 2.54
15 6 PC 1.0
15 8 MI 2.54
24 0 4.5 4.5
1.  .1  20.  .05  35.  2.5  2.  1.15
22 0. 20. 0 35. 0 0 0
22 .1 20 .05 35
22 .1 0. .05 0. 0. 0. 0.
22 0 0 0 0 0 1 .7746
22 .1 20 .05 35 0 1 .7746
22 0. 20. 0. 35. 0 1. .7746
-17.000000 -0.000000
 13.000000  2.000000
6.          4.          0.10        0.05
  2.000000  0.000000
  4.000000   .393110-15.45     0.
  2.000000-23.000000
  3.000000   .151000
  5.010000   .360000-4.676     3.75
-8.         0.          0.          0.          0.          0.          0.          100.
  3.000000   .050000
5.01 .2 5.8645 3.75
  3.000000   .409450
10. -2. 2. 0. .001
10. -4. 4. 0. .001
23 -.45 .0006 4 1.378 .9927 .7746
23 -.45 .0006 4 1.378 .9927 .7746
23 -.45 .0006 4 1.378 .9927 .7746
23 -.45 .0006 4 1.378 .9927 .7746
  3.000000   .300000
-6 0 2 0 PC2
5.01 .2 4.1 3.75
  3.000000   .051970
  5.010000   .200000-3.8       3.75
-8.         0.          0.          0.          0.          0.          0.          102.
  3.000000   .268740
  2.000000-13.500000
  4.000000   .420000-16.95     0.
  2.000000-13.500000
  3.000000   .208940
 18.000000   .280   0.00       3.75
 3.          .10
 6.          4.          1.0         1.0
10. -1. 2. 0. .001
  3.000000   .568460
  3.000000   .060000
10.          4.          3.          0.          .001
 13.000000  4.000000
  3.000000   .060000
 13.000000  4.000000
 24 1234 2.5 25. 1.5 30. $ SCALES X=2.5, XP=25., Y=1.5, YP=30.0
 SENTINEL
  Q1 MISALIGNMENT SY=10 MR
  2
 FIX
 A ALIN1 1 8
 A ALIN1 3 10

 SENTINEL
  Q1 MISALIGNMENT Y=0.1 IN
  2
 A ALIN1 3 0 0.1 $ ALTER 3RD AND 4TH NUMBERS OF ALIN1

 SENTINEL
  Q3-4 MISALIGNMENT SY=10 MR
  2
 A ALIN1 1 -8
 A RC2 1 6
 A ALIN2 1 8
 A ALIN2 3 10

 SENTINEL
  Q3-4 MISALIGNMENT Y=0.1 IN
  2
 A ALIN2 3 0
 A ALIN2 4 .1

 SENTINEL
 SENTINEL
  Q1 MISALIGNMENT Z ROTATION = 100 MR
  2
 A ALIN1 4 0
 A ALIN1 7 100

 SENTINEL
  Q3-4 MISALIGNMENT Z ROTATION = 100 MR
  2
 A ALIN2 4 0
 A ALIN2 7 100

 SENTINEL
```

Fig. 5-30. TRANSPORT input data for study of magnet misalignments.

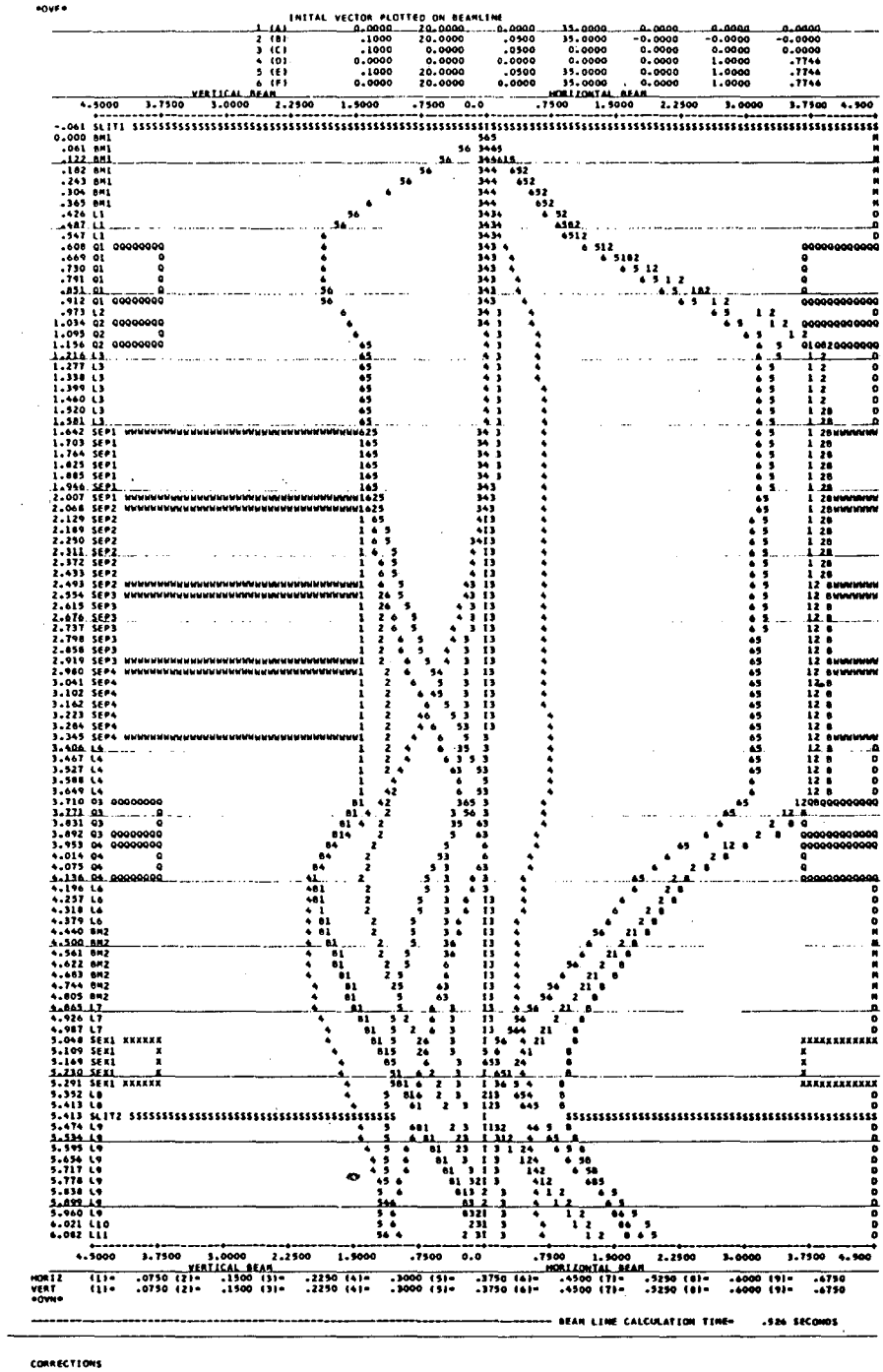

Fig. 5-31. Beam line graph for example 6.

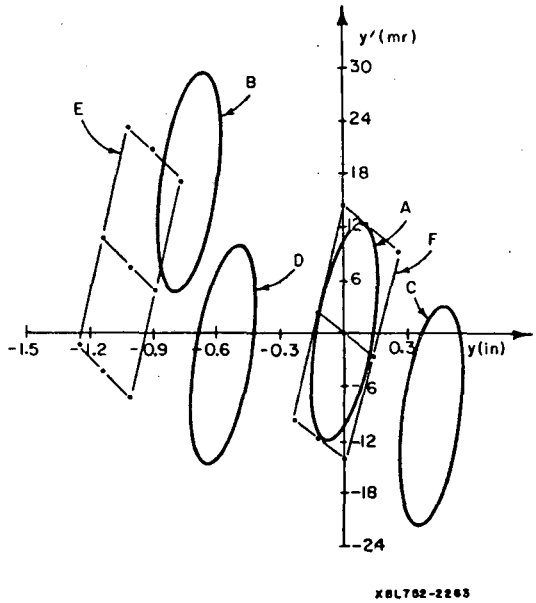

Fig. 5-32. Vertical phase space showing effect of the misalignment of quadrupoles Q1 and Q3-Q4. A) No misalignment of any quadrupoles, B) Q1 misaligned by $\Delta y' = 10$ mr, C) Q1 misaligned by $\Delta y = 0.1$ inch, D) Q3-Q4 misaligned by $\Delta y' = 10$ mr, E) separated vectors with no misalignments, and F) non-separated vectors with no misalignments.

```
OPTION 3 SEARCH
0
13 2
13 2
1 1 10 1 10 0 0 9.5
13 2
3 5
5.02 .75 7.5 5
3 .375
5.01 1.5 -7.5 5
3 .375
5.02 .75 7.5 5.
3. 4.25
10 2 1 0 .01
10 4 3 0 .01
13 1
SENTINEL
OPTION 3 SEARCH CHI-TABLE VARIABLES 1 AND 2
3
1 5 10 1 0 10
2 -4 -10 -2

SENTINEL
```

Fig. 5-33. TRANSPORT input data for determining complete set of waist to waist transfers. Option 3 must be used to step over the separatrices in the multi-dimensional chi-square space.

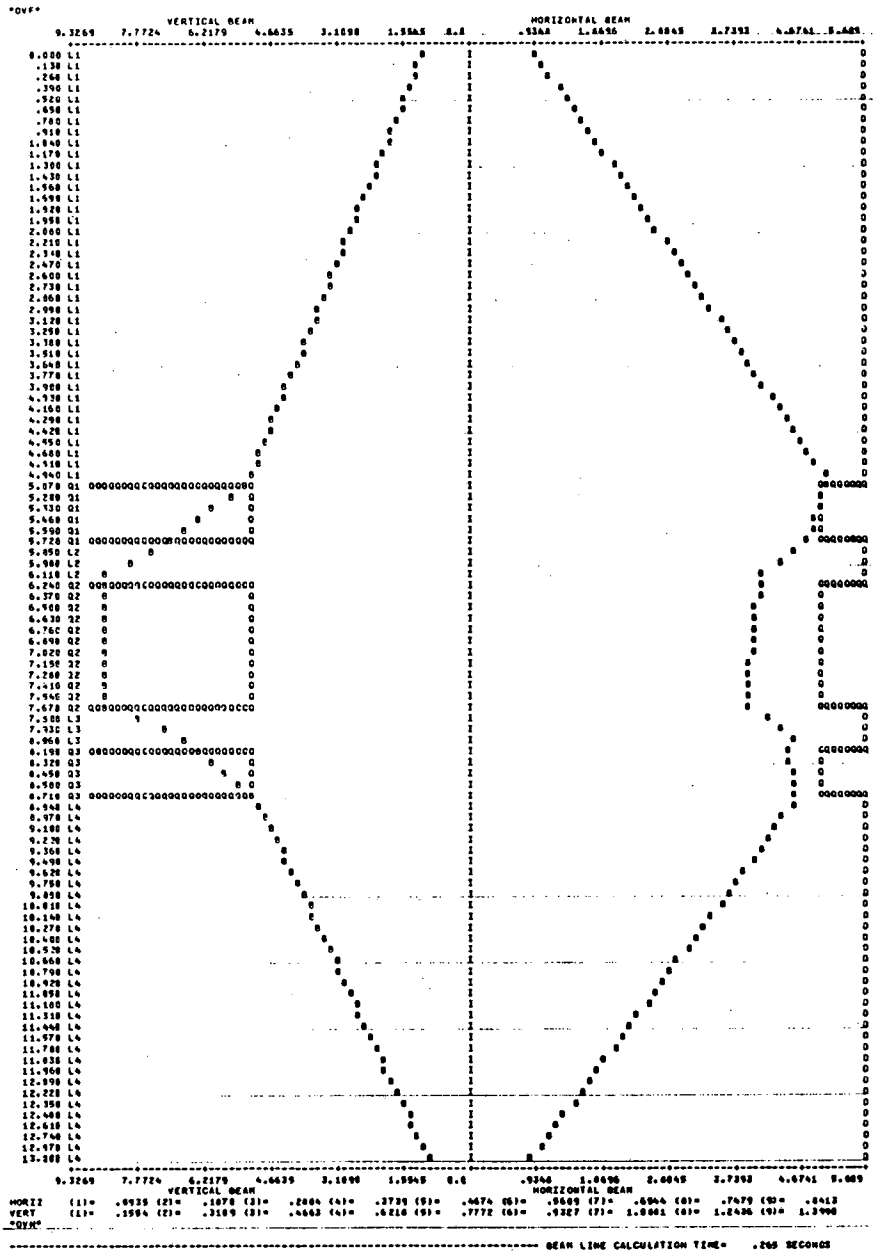

Fig. 5-34. Beam line trace for example 7.

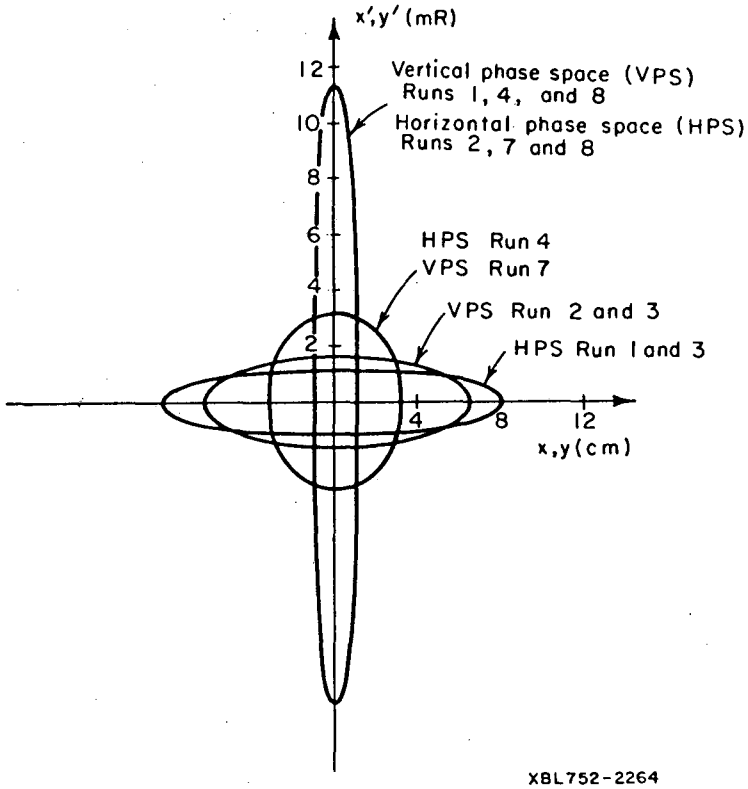

Fig. 5-35. Eigen-ellipse for the solutions of waist to waist transformations of the symmetric triplet lense of example 7. The quadrupole excitations are given for the various runs shown in Table 17.

```
$  BREAK UP CROWE LINE FOR USE WITH INPUTED 25 ELEMENT IN SECOND ORDER
 BAER-CROWE BEAMLINE AT LEP-LASL CHANNEL
 0
15 0 1 1
22 OR7
22 OR5 1.
22 .05 0 1.06
22 0 40 0 110
1.0  .05  40.0 1.06 110.0  0.0  2.80   0.2  BEAM1
-13 2 SIOFF
13 2
16. 29. -1. VARMIT
24  0 30 30 0 1 6
24 1 -.05 .05 -1.06 1.06 $ TARGET SIZE
24 4 .18 .22 .01 $ E SPECTRUM
3.  0.62  D1
5.00  0.51  -2.58358  10.16  Q1
 3. 0.35 SEP1
5.00  0.7  1.54221  14.  Q2
6 0 1 1 UPDATE
3.  0.55  D2
16 4 25
16. 5.  7.62  GAP
16.  7.  .26   FRIN1
16. 8.  4.4  FRIN2
16. 12. 0.5109 R1
16. 13. -.7871 P2
16 21 2 $  4. L. ANGLE. N.
2 30 0 PFR1
4 1 60 0  BEND1
2 30 0 PFR11
3.  1.6  D3
16. 12.  1.2692 R3
16. 13. .9772 R4
2 -30 0 PFR2
4 1 -60 0 BEND2
2 -30 0 PFR22
 3.    .65  D4
 13. 4.  MTX1
13. 42. $  PRINT T MATRIX WIEGTED BY THE SIGMA MATRIX VALUES
 3.    .65  D4
16. 12. .9772 R4
16. 13.  1.2692 R3
2 -30 0 PFR22
4 1 -60 0 BEND3
2 -30 0 PFR2
3.  1.6  D3
16. 12. -.7871 R2
16. 13. 0.5109 R1
2 30 0 FFR11
4 1 60 0 BEND4
2 30 0 PFR1
3.  0.55  D2
13 1
13 4
13 42


5 .7 1.1244 14 Q3
 3. 0.35 SEP1
5 .51 -1.0613 10.16 Q4
3 2
3 .7
6 4 2 4 CHAMBR
$  CHAMBER HERE -P 2.0CM BY -+4 CM
13 1
13 4
13 -42
3 .7
3 2
5 .5 1.6215 10 Q5
3 .25
5 .5 -1.6608 10 Q6
3 1
3 1
3 .3
$  LT2 TARGET 2.7 X 4.1 CM FULL SIZE
6 4 2.05 1.35 LT2
$  LT2 TARGET HERE 2.7 X 4.1 CM FULL SIZE
$  SINCE TRANSPORT IS IN REVERSED PLANE
$    X=-+ 2.05 CM     Y=-+1.35 CM
13. -42.  $  PRINT T MATRIX WIEGHTED BY THE SIGMA MATRIX
 13. 4.  MTXE
3 .43 EXTRA
3 .7 EXTRA
SENTINEL
```

Fig. 5-36. Transport input data for example 8.

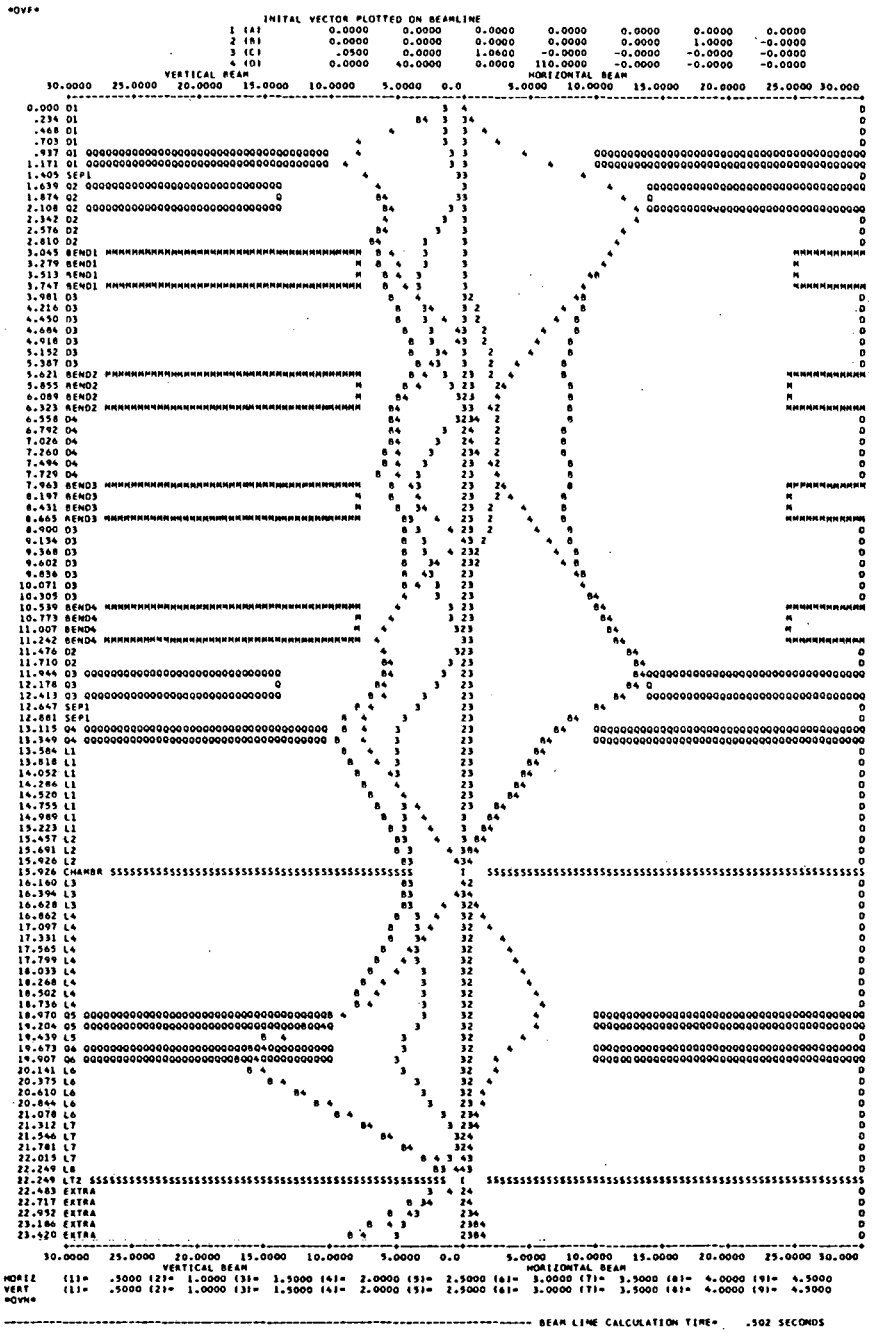

Fig. 5-37. Beam line graph for the LEP channel. Note the use of the vectors for determining the beam spread produced by a momentum deviation and determining the locations of waists by displaying the points of phase reversal.

```
 BEAR-CROWE BEAMLINE WITH 25 ELEMNT INPUT OF BENDING MAGNETS IN 2-ND ORDER
0
15 0 1 1
22 OR7
1 .05 40 1.06 110 0 2.8 .2
17
13 2
24 0 30 30 0 1 6
3 .62
5 .51 -2.58358 10.16
3 .35
5 .7 1.54221 14
13 1
16 17 9.6
25 MAGNETS 52 12345
1 .8908 OR4
0 1 OR4
0 0 .9950 .0004 0 0
0 0 -4.835 .9990 0 0
0 0 0 0 1 0
-.1811 -.1475 -.03256 0 0 .09842 0 0 -1.707E-2 2.669E-3 OR5
        -.8339 -.3437 0 0 0 -.9992
-.4067 -.3623 -.08761 0 0 .1969 0 0 -.02929 .006028 OR5 -1.858 -.8209 OR3 -2.235
-OR3 .02922 .00892 0 -.01206 -.00537 OR9 .09951 -.04099 0 0
OR3 .2519 .1122 0 .02922 .01711 OR9 1.617 .09951 0 0
.09162 .08065 .01844 0 0 -.1032 0 0 .009997 -.002065
          OR5  .4434 .1967 OR3 .3996    $ T(5,J,K)
13 1
13 8
13 42
13 48
5 .7 1.1244 14
3 .35
5 .51 -1.0613 10.16
3 2
3 .7
6 4 2 4
13 1
13 42
3 .7
3 2
5 .5 1.6215 10
3 .25
5 .5 -1.6608 10
3 1
3 1
3 .3
6 4 2.05 1.35 LT2
13 1
13 42
SENTINEL
```

Fig. 5-38. Transport input for the same beam line of Figure 5-36 where the bending magnet systems has been replaced by its first and second order transformation matrix.

```
DATE=6/21/74                                                                                                CASE NUMBER   4-  0-F

BEAR-CROWE BEAMLINE WITH 25 ELEMNT INPUT OF BENDING MAGNETS IN 2-ND ORDER
    1(UNIT1 )      15.0        0.0        1.0        1.0
    5(VEC1  )   22.000000    1.000000
               22.000000    0.000000   0.000000   0.000000   0.000000   0.000000   0.000000   0.000000
    7(BEAM1 )    1.000000     .050000  40.000000   1.060000 110.000000   0.000000   2.800000     .200000
   15(SEC1  )   17.000000   -0.000000  -0.000000  -0.000000
   19(I01   )   13.000000    2.000000
   21(PLOT1 )   24.000000    0.000000  30.000000  30.000000   0.000000   1.000000   6.000000
   28(L1    )    3.000000     .620000
   30(Q1    )    5.000000     .510000  -2.583580  10.160000
   34(L2    )    3.000000     .350000
   36(Q2    )    5.000000     .700000   1.542210  14.000000
   40(I02   )   13.000000    1.000000
   42(DA1   )   16.000000   17.000000   9.600000
   45(MAT1  )      25.0      MAGNET     52.0    12345.0
   49(I03   )   13.000000    1.000000
   51(I04   )   13.000000    8.000000
   53(I05   )   13.000000   42.000000
   55(I06   )   13.000000   48.000000
   57(Q3    )    5.000000     .700000   1.124400  14.000000
   61(L3    )    3.000000     .350000
   63(Q4    )    5.000000     .510000  -1.061300  10.160000
   67(L4    )    3.000000    2.000000
   69(L5    )    3.000000     .700000
   71(SLIT1 )    6.000000    4.000000   2.000000   4.000000
   75(I07   )   13.000000    1.000000
   77(I08   )   13.000000   42.000000
   79(L6    )    3.000000     .700000
   81(L7    )    3.000000    2.000000
   83(Q5    )    5.000000     .500000   1.621500  10.000000
   87(L8    )    3.000000     .250000
   89(Q6    )    5.000000     .500000  -1.660800  10.000000
   93(L9    )    3.000000    1.000000
   95(L10   )    3.000000    1.000000
   97(L11   )    3.000000     .300000
   99(LT2   )    6.000000    4.000000   2.050000   1.350000
  103(I09   )   13.000000    1.000000
  105(I010  )   13.000000   42.000000
```

Fig. 5-39. Transport data array for data input of Figure 5-38.

```
HISTOGRAMS
4
22 -.03 .03 .015 -24 24 8 -12341.
-.6  .6  .6  -60  60  20
24 12
24 34
24 13
24 1
24 2
24 3
24 4
$  PLUS 1.0 PERCENT MOMENTUM
22 OR5 1.  0.
22 -.03  .03  .015  -24.  24  8  -12341.
-.6  .6  .6  -60  60  20
24 12
24 13
$  MINUS 1.0 PERCENT MOMENTUM
22 OR5 -1
22 -.03  .03  .015  -24  24  8  -12341
-.6  .6  .6  -60  60  20
24 12
24 13
ELLIPSE 0.05 40 1.06 110.0  1000 -12341 $ X-XP-Y-YP RANDOM BOUNDARY 1000 POINTS
24 1
24 2
24  3
24 4
24 13
24 12
24 34
ELLIPSE 0.05  40.0  500 -121 $ X-XP RANDOM BOUNDARY  500 POINTS
24 1
24 2
24 12

SENTINEL
```

Fig. 5-40. Data input for TRANSPORT to calculate particle histograms and scatter plots shown in Figures 5-41, 42, and 43.

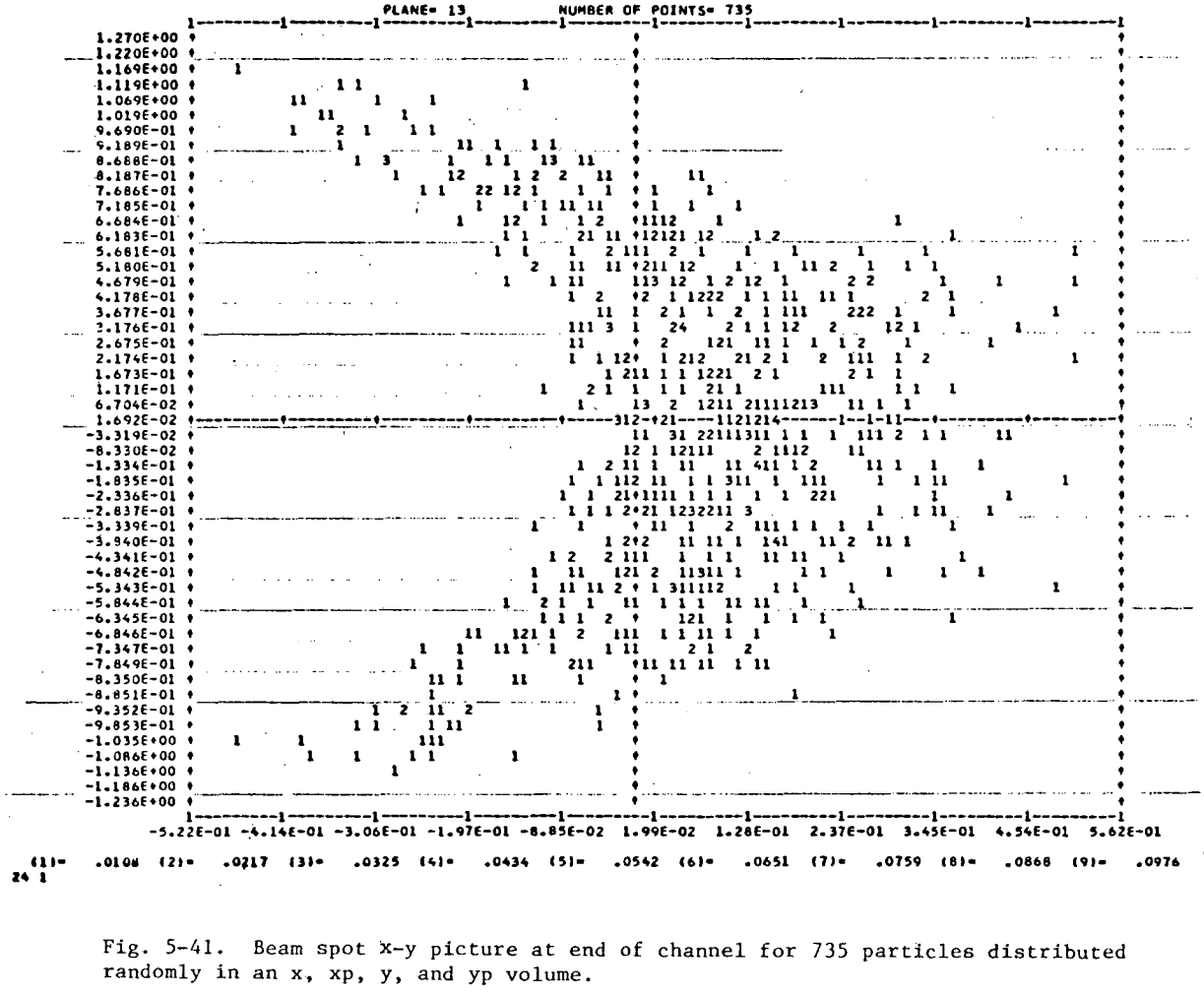

Fig. 5-41. Beam spot x-y picture at end of channel for 735 particles distributed randomly in an x, xp, y, and yp volume.

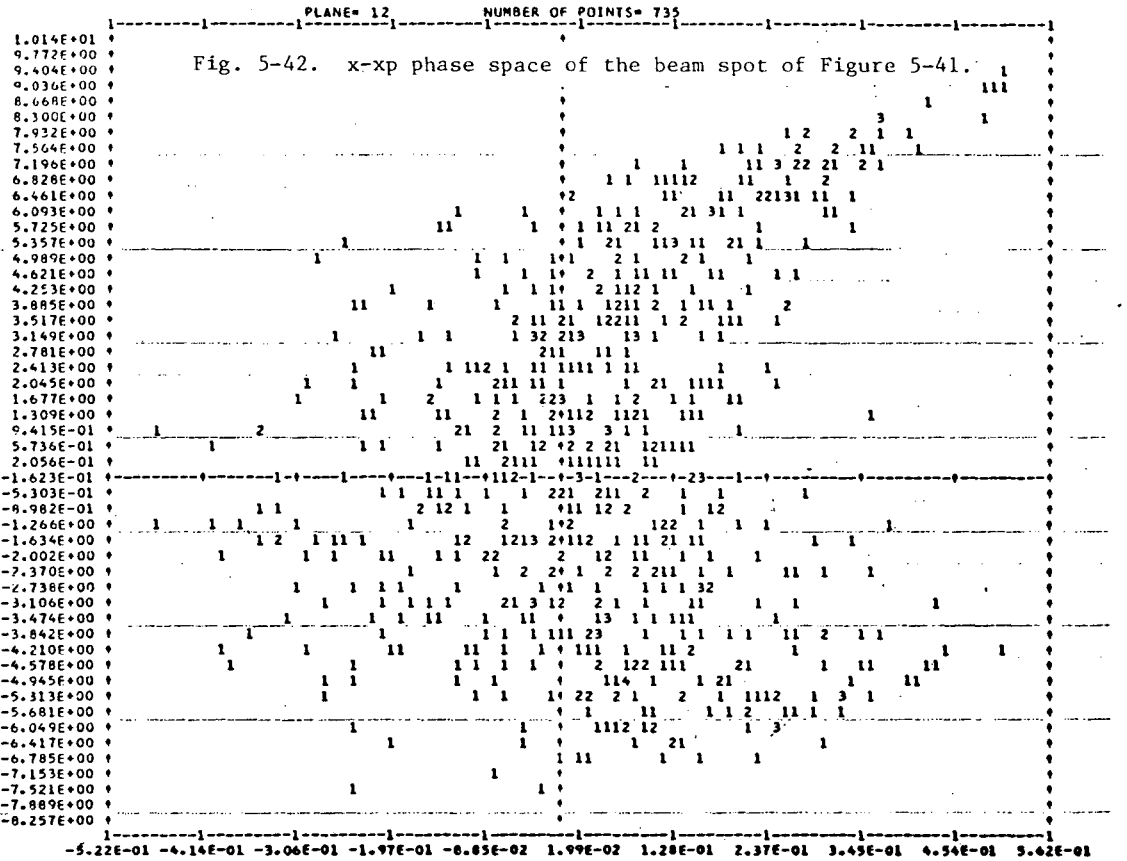

Fig. 5-42. x-xp phase space of the beam spot of Figure 5-41.

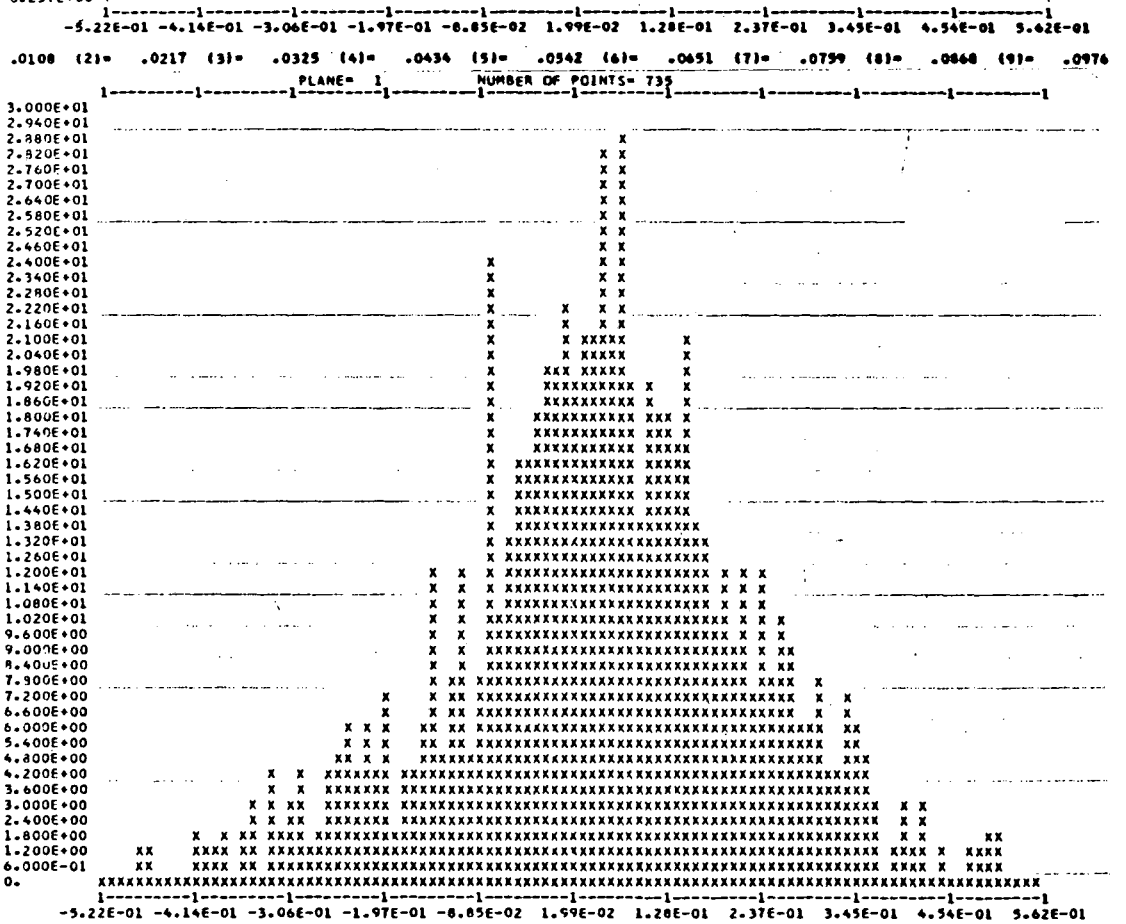

Fig. 5-43. x-axis histogram for the particles of Figures 5-40, 41.

```
LONG PEP A72P BEAM LINE, START
$72A 200 GEV PROTONS (WITH 15 GEV ELECTRONS) 2/13/74 DATA WITH 25 ELEMNT
0
15 0 1 1
24 0 2.4 1.8 1.0
13 2
21 -8 -100 100 $ SET LIMITS FOR QUADRUPOLE FIELD VARIATION
13 34
16 16 .15 $ SCALE QUAD APERTURES
16 27 .1
16 29 -1 $ TURN ON VARMIT
22 .1562
22 0 .481
22 0 0 .05162
22 0 0 0 .364
22 OR5 .1
1 .1562 .481 .05162 .364 0 0 200
12 OR15
7 0 0 0 0 0 .1
13 1 START $ PRINT BEAM
13 2 LINK1
3 10
5 1.5 -9.779987 10
3 .5
5 1.5 8.759350 10
3 .5
20 90
4 5.5 -3.637341 0
2 -.171815 0
3 .5
2 .171815 0
4 2 10.002688 0
3 .5
4 2 17.004528 0
2 .292084 0
3 .5
2 -.292084 0
4 2 -17.004528 0
20 -90
3 .500037
5 1.25 -40 10
13 4
5 1.25 -40 10
3 1.5
5.04 1.25 36.81715 10
5.04 1.25 36.81715 10
13 4
3 28.842317
5 1.4 -17.874085 10
3 .4
5 1.4 16.259398 10
3 1.242387
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1.342387
5 1.2 -51.702136 10
3 1.342387
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
13 2 END1
73.
```

Fig. 5-44. Data input to TRANSPORT for the first segment of the PEP beam Lattice.

DATE=9/27/74 CASE NUMBER 4- 0-F

LONG PEP A72P BEAM LINE, START

1(INITI)	15.0	0.0	1.0	1.0					
5(PLOT1)	24.000000	0.000000	2.400000	1.800000	1.000000	-0.000000	-0.000000		
12(I01)	13.000000	7.000000							
14(STRY1)	21.000000	-8.000000	-100.000000	100.000000					
18(I02)	13.000000	34.000000							
20(DA1)	16.000000	16.000000	.150000						
23(DA2)	16.000000	27.000000	.100000						
26(DA3)	16.000000	29.000000	-1.000000						
29(VEC1)	22.000000	5.000000							
	22.000000	.156200	-0.000000	-0.000000	-0.000000	-0.000000	-0.000000	-0.000000	
	22.000000	0.000000	.481000	-0.000000	-0.000000	-0.000000	-0.000000	-0.000000	
	22.000000	0.000000	0.000000	.051620	-0.000000	-0.000000	-0.000000	-0.000000	
	22.000000	0.000000	0.000000	0.000000	.364000	-0.000000	-0.000000	-0.000000	
	22.000000	0.000000	0.000000	0.000000	0.000000	0.000000	.100000	-0.000000	
31(BEAM1)	1.000000	.156200	.481000	.051620	.364000	0.000000	0.000000	200.000000	
39(TIL1)	12.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	
		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
55(AXIS1)	7.000000	0.000000	0.000000	0.000000	0.000000	0.000000	.100000		
62(START)	13.000000	1.000000							
64(LINK1)	13.000000	2.000000							
66(L1)	3.000000	10.000000							
68(Q1)	5.000000	1.500000	-9.779987	10.000000					
72(L2)	3.000000	.500000							
74(Q2)	5.000000	1.500000	8.759350	10.000000					
78(L3)	3.000000	.500000							
80(POT1)	20.000000	90.000000							
82(BM1)	4.000000	5.500000	-3.637341	0.000000					
86(FF1)	2.000000	-.171815	0.000000						
89(L4)	3.000000	.500000							
91(FF2)	2.000000	.171815	0.000000						
94(BM2)	4.000000	2.000000	10.002688	0.000000					
98(L5)	3.000000	.500000							
100(BM3)	4.000000	2.000000	17.004528	0.000000					
104(FF3)	2.000000	.292084	0.000000						
107(L6)	3.000000	.500000							
109(FF4)	2.000000	-.292084	0.000000						
112(BM4)	4.000000	2.000000	-17.004528	0.000000					
116(POT2)	20.000000	-90.000000							
118(L7)	3.000000	.500037							
120(Q3)	5.000000	1.250000	-40.000000	10.000000					
124(I03)	13.000000	4.000000							
126(Q4)	5.000000	1.250000	-40.000000	10.000000					
130(L8)	3.000000	1.500000							
132(Q5)	5.040000	1.250000	36.817150	10.000000					
136(Q6)	5.040000	1.250000	36.817150	10.000000					
140(I04)	13.000000	4.000000							
142(L9)	3.000000	28.842317							
144(Q7)	5.000000	1.400000	-17.874085	10.000000					
148(L10)	3.000000	.400000							
150(Q8)	5.000000	1.400000	16.259398	10.000000					
154(L11)	3.000000	1.242387							
156(REP1)	9.000000	2.000000							
158(L12)	3.000000	.150000							
160(FF5)	2.000000	.937500	0.000000						
163(BM5)	4.000000	4.960500	44.011120	0.000000					
167(FF6)	2.000000	.937500	0.000000						
170(L13)	3.000000	.150000							
172(REP2)	9.000000	0.000000							
174(L14)	3.000000	1.342387							
176(Q9)	5.000000	1.200000	-51.702136	10.000000					
180(L15)	3.000000	1.342387							
182(REP3)	9.000000	2.000000							
184(L16)	3.000000	.150000							
186(FF7)	2.000000	.937500	0.000000						
189(BM6)	4.000000	4.960500	44.011120	0.000000					
193(FF8)	2.000000	.937500	0.000000						
196(L17)	3.000000	.150000							
198(REP4)	9.000000	0.000000							
200(END1)	13.000000	2.000000							

Fig. 5-45. Data array for the data of Figure 5-44.

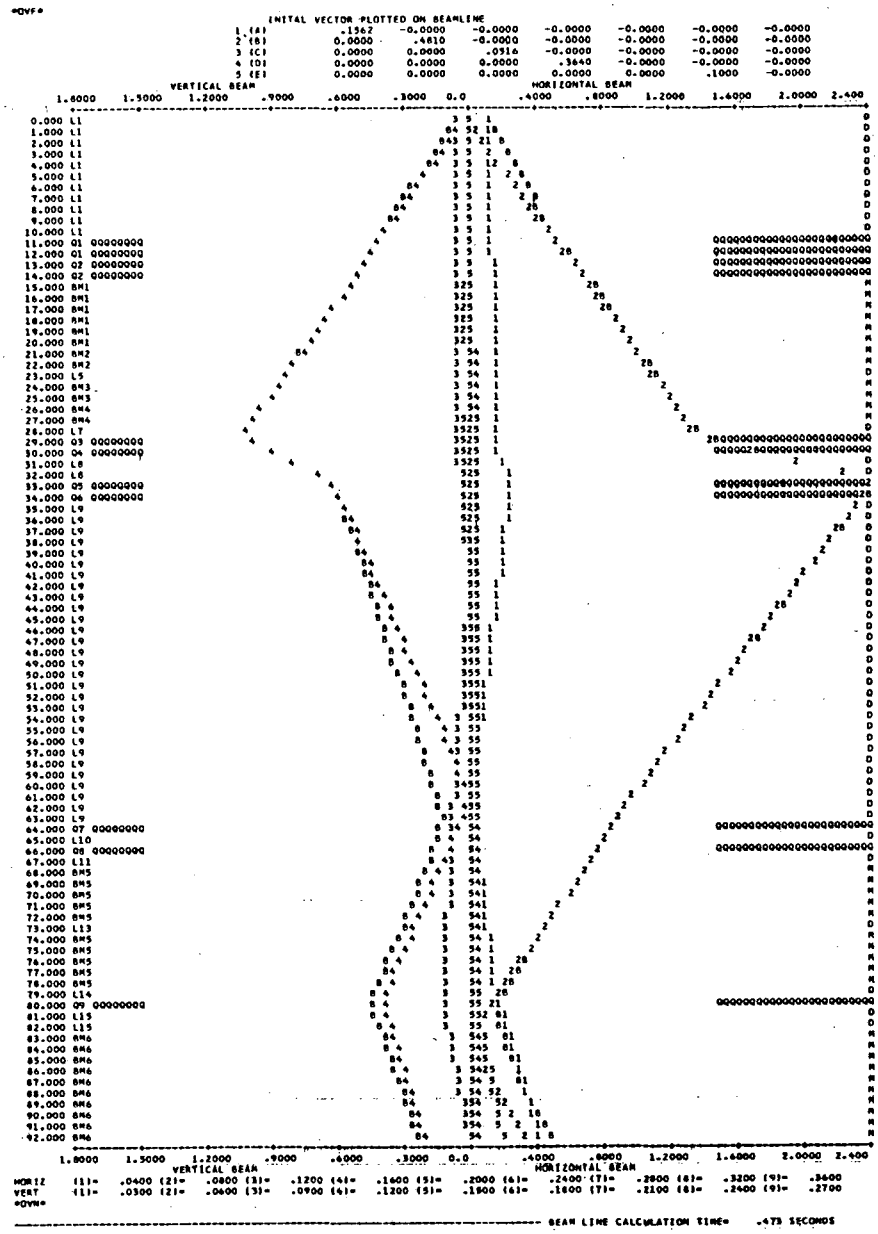

Fig. 5-46. Beam line trace for the first segment of the PEP beam line.

```
LONG PEP A72P BEAM LINE, CONTINUED
1
-1 $ CONTINUE BEAM, VECTORS, RC2 AND R3 MATRICES
2
0 LINK1 END1

13 2 LINK2
3 1.342387
5 1.2 64.441152 10
3 1.342387
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1.342387
5 1.2 -41.875512 10
3 1.342387
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1.342387
5 .6 52.158396 10
13 4
13 1
10 21 1 4.6048 .00001 BETAX $ CONSTARINT ON BETAX FUNCTION
10 22 1 0 .001  $ CONSTRAIN ALPHAX
10 23 3 1.1872 .0001 $ BETAY
10 24 3 0 .0001 $ ALPHAY
10 21 6 2.72811 .0001
10 22 6 0 .00001 ETAXP
5 .6 52.158396 10
3 1.342387
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1.342387
5 .6 -48.223183 10
13 1 END $ PRINT BEAM
13 2 END2
73.
LONG PEP A72P BEAM LINE, END
1
-1 $ CONTINUE BEAM, VECTORS, RC2 AND R3 MATRICES
2
0 LINK2 END2

13 2 LINK3
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1
3 1
9 2
3 .15
2 .93750 0
4 4.9605 44.011120 0
2 .93750 0
3 .15
9 0
3 1
13 2 END3
73.
73.
```

Fig. 5-47. Data input to TRANSPORT to continue the PEP beam line.

DATE=9/27/74 CASE NUMBER 5- 0-F

LONG PEP A72P BEAM LINE, CONTINUED

1(INIT1)	15.0	0.0	1.0	1.0					
5(PLOT1)	24.000000	0.000000	2.400000	1.800000	1.000000	-0.000000	-0.000000		
12(I01)	13.000000	2.000000							
14(STRY1)	21.000000	-8.000000	-100.000000	100.000000					
18(I02)	13.000000	34.000000							
20(DA1)	16.000000	16.000000	.150000						
23(DA2)	16.000000	27.000000	.100000						
26(DA3)	16.000000	29.000000	-1.000000						
29(VEC1)	22.000000	5.000000							
	22.000000	-.396166	-.210335	-.000000	.000000	.023552	0.000000	-0.000000	
	22.000000	-.288406	-.342770	-.000000	.000000	-.024321	0.000000	-0.000000	
	22.000000	-.000000	-.000000	-.023082	.102213	-.000000	0.000000	-0.000000	
	22.000000	-.000000	-.000000	-.220734	.163421	.000000	0.000000	-0.000000	
	22.000000	.218652	.175539	-.000000	.000000	-.009742	.100000	-0.000000	
31(BEAM1)	1.000000	.490026	.402159	.221937	.192753	.033856	0.000000	200.000000	
39(TIL1)	12.000000	.924472	.000000	.000000	-.000000	-.000000	-.898377	-.139610	
		.248450	-.000000	.000000	0.000000	0.000000	0.000000	0.000000	0.000000
55(AXIS1)	7.000000	.218652	.175539	-.000000	.000000	-.009742	.100000		
62(START)	13.000000	1.000000							
64(LINK2)	13.000000	2.000000							
66(L18)	3.000000	1.342387							
69(Q10)	5.000000	1.200000	64.441152	10.000000					
72(L19)	3.000000	1.342387							
74(REP5)	9.000000	2.000000							
76(L20)	3.000000	.150000							
78(FF9)	2.000000	.937500	0.000000						
81(BM7)	4.000000	4.960500	44.011120	0.000000					
85(FF10)	2.000000	.937500	0.000000						
88(L21)	3.000000	.150000							
90(REP6)	9.000000	0.000000							
92(L22)	3.000000	1.342387							
94(Q11)	5.000000	1.200000	-41.875512	10.000000					
98(L23)	3.000000	1.342387							
100(REP7)	9.000000	2.000000							
102(L24)	3.000000	.150000							
104(FF11)	2.000000	.937500	0.000000						
107(BM8)	4.000000	4.960500	44.011120	0.000000					
111(FF12)	2.000000	.937500	0.000000						
114(L25)	3.000000	.150000							
116(REP8)	9.000000	0.000000							
119(L26)	3.000000	1.342387							
120(Q12)	5.000000	.600000	52.158396	10.000000					
124(I05)	13.000000	4.000000							
126(I06)	13.000000	1.000000							
128(ETAX)	10.000000	21.000000	1.000000	4.604800	.000010				
133(CON1)	10.000000	22.000000	1.000000	0.000000	.001000				
138(CON2)	10.000000	23.000000	3.000000	1.187200	.000100				
143(CON3)	10.000000	24.000000	3.000000	0.000000	.000100				
148(CON4)	10.000000	21.000000	6.000000	2.728110	.000100				
153(ETAXP)	10.000000	22.000000	6.000000	0.000000	.000010				
159(Q13)	5.000000	.600000	52.158396	10.000000					
162(L27)	3.000000	1.342387							
164(REP9)	9.000000	2.000000							
166(L28)	3.000000	.150000							
168(FF13)	2.000000	.937500	0.000000						
171(BM9)	4.000000	4.960500	44.011120	0.000000					
175(FF14)	2.000000	.937500	0.000000						
178(L29)	3.000000	.150000							
180(REP10)	9.000000	0.000000							
182(L30)	3.000000	1.342387							
184(Q14)	5.000000	.600000	-48.223183	10.000000					
188(END)	13.000000	1.000000							
190(END2)	13.000000	2.000000							

Fig. 5-48. Data array for the continuation of the PEP beam line. Note that the beam data, tilt data and vector data has been updated by the continuation.

```
*OVF*
                                  INITAL VECTOR PLOTTED ON BEAMLINE
                                1 (A)        -.3962     -.2103     -.0000      .0000      .0236     0.0000    -0.0000
                                2 (B)        -.2884     -.3428     -.0000      .0000     -.0243     0.0000    -0.0000
                                3 (C)        -.0000     -.0000     -.0231      .1022     -.0000     0.0000    -0.0000
                                4 (D)        -.0000     -.0000     -.2207      .1634      .0000     0.0000    -0.0000
                                5 (E)         .2187      .1755     -.0000      .0000     -.0097      .1000    -0.0000
                         VERTICAL BEAM                                          HORIZONTAL BEAM
      1.8000    1.5000    1.2000     .9000     .6000     .3000    0.0        .4000     .8000    1.2000    1.6000    2.0000  2.400
        +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+
  0.000 L18                                                 84      54   5  2 1 8                                                D
  1.000 L18                                                  84     54   5   2 1 8                                              D
  2.000 Q10 QQQQQQQ                                          84    254    5  2 1 8                          QQQQQQQQQQQQQQQQQQQQQQQQ
  3.000 Q10 QQQQQQQ                                          84    514    5  2 1 8                          QQQQQQQQQQQQQQQQQQQQQQQQ
  4.000 L19                                                  84    514   5   21 8                                                D
  5.000 BM7                                                 8 4    514   5   2  8                                               M
  6.000 BM7                                                 84    3514   5   2 8                                               M
  7.000 BM7                                                 84    3514   5  128                                               M
  8.000 BM7                                                 84    3514   5  12 8                                              M
  9.000 BM7                                                8 4    3 514  5 1 28                                               M
 10.000 BM7                                                8 4    3 514  5 1 28                                               M
 11.000 BM7                                                84     3 514  51  2                                               M
 12.000 BM7                                                84    3  514  5   2                                               M
 13.000 BM7                                               8 4    3  514 51  82                                               M
 14.000 BM7                                               8 4    3  514 5   82                                               M
 15.000 L22                                               8 4    3   51415   2                                               D
 16.000 L22                                               8 4    3   541 5  82                                               D
 17.000 Q11 QQQQQQQ                                       8  4   3   541 5  82                          QQQQQQQQQQQQQQQQQQQQQQQQ
 18.000 L23                                               8 4    3   54  5   82                                               D
 19.000 BM8                                               8  4 3   541 5   82                                               M
 20.000 BM8                                                8 4 3   541  5   82                                               M
 21.000 BM8                                                8  43   54 1 5   82                                               M
 22.000 BM8                                                8 43    54  15    2                                               M
 23.000 BM8                                                8  4    54  15    82                                              M
 24.000 L25                                                8  4    54   5     2                                              D
 25.000 BM8                                                 8 4    54    5    28                                              M
 26.000 BM8                                                 8 34   54    5     2                                              M
 27.000 BM8                                                 8 34   54    51    28                                             M
 28.000 BM8                                                  83 4 54     51    29                                             M
 29.000 BM8                                                  83 4 54     51    28                                             M
 30.000 L26                                                  83  454     5 1   2 8                                           D
 31.000 Q12 QQQQQQQ                                           3  454     5 1   2 8                          QQQQQQQQQQQQQQQQQQQQQQQQ
 31.000 Q13 QQQQQQQ                                                I                                        QQQQQQQQQQQQQQQQQQQQQQQQ
 32.000 L27                                                  83   54     5 1   2 8                                           D
 33.000 L27                                                  3    54     5 1  2 8                                           D
 34.000 BM9                                                  3    54     5  1 2 8                                           M
 35.000 BM9                                                 3     54     5  12  8                                           M
 36.000 BM9                                                 3     54     5  12 8                                            M
 37.000 BM9                                                 3     54    5 12 8                                              M
 38.000 BM9                                                3      54    5  2  8                                             M
 39.000 BM9                                                3      54    5 21 8                                              M
 40.000 BM9                                               3       54    5 21 8                                              M
 41.000 BM9                                               3       54   52 18                                                M
 42.000 BM9                                               3       54    5  18                                               M
 43.000 BM9                                              3        454  5  18                                               M
 44.000 L30                                              3        454  5  18                                               D
 45.000 L30                                              3        454 25  1                                                 D
 45.000 Q14 QQQQQQQ                                                I                                        QQQQQQQQQQQQQQQQQQQQQQQQ
        +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+
      1.8000    1.5000    1.2000     .9000     .6000     .3000    0.0        .4000     .8000    1.2000    1.6000    2.0000  2.400
                         VERTICAL BEAM                                          HORIZONTAL BEAM
HORIZ    (1)=   .0400 (2)=   .0800 (3)=   .1200 (4)=   .1600 (5)=   .2000 (6)=   .2400 (7)=   .2800 (8)=   .3200 (9)=   .3600
VERT     (1)=   .0300 (2)=   .0600 (3)=   .0900 (4)=   .1200 (5)=   .1500 (6)=   .1800 (7)=   .2100 (8)=   .2400 (9)=   .2700
```

Fig. 5-49. Beam line trace for the second segment of the PEP beam.

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