ACCELERATION: Type code 11.0

An energy gain is reflected in both the divergence and the width of the beam. This element provides a simulation of a travelling wave linear accelerator energy gain over a field free drift length (i.e. no externally applied magnetic field).

There are five parameters:

1 - Type code 11.0
2 - Accelerator length (metres).
3 - Energy gain (GeV).
4 - ϕ (phase lag in degrees).
5 - λ (wavelength in cm).

The new beam energy is printed as output.

The energy of the reference trajectory is assumed to increase linearly over the entire accelerator length. If this is not the case, an appropriate model may be constructed by combining separate 11.0 elements. An 11.0 element with a zero energy gain is identical to a drift length.

None of the parameters may be varied.

Second-order matrix elements have not been incorporated in the program for the accelerator section.

The units of parameters 2, 3, and 5 are changed by 15. 8., 15. 11., and 15. 5. type code entries respectively.

Accelerator section matrix

$$\begin{bmatrix} 1 & \left[L \dfrac{E_0}{\Delta E \cos\phi} \ln\left(1 + \dfrac{\Delta E \cos\phi}{E_0}\right)\right] & 0 & 0 & 0 & 0 \\ 0 & \dfrac{E_0}{E_0 + \Delta E \cos\phi} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & \left[L \dfrac{E_0}{\Delta E \cos\phi} \ln\left(1 + \dfrac{\Delta E \cos\phi}{E_0}\right)\right] & 0 & 0 \\ 0 & 0 & 0 & \dfrac{E_0}{E_0 + \Delta E \cos\phi} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \left(\dfrac{\Delta E \sin\phi}{E_0 + \Delta E \cos\phi}\right)\left(\dfrac{2\pi}{\lambda}\right) & \dfrac{E_0}{E_0 + \Delta E \cos\phi} \end{bmatrix}$$

Definitions: L = effective length of accelerator sector

E_0 = particle energy at start of sector

ΔE = energy gain over sector length

ϕ = phase lag of the reference particle behind the crest of the accelerating wave, i.e. if ϕ is positive then for some $\ell > 0$ the particles having this value are riding the crest of the wave; the units of ϕ are degrees

λ = wavelength of accelerating wave; the units of λ are those of ℓ (normally cm).

This matrix element assumes that $E_0 \gg m_0c^2$ (fully relativistic).

BEAM (rotated ellipse): Type code 12.0

To allow the output beam from some point in a system to become the input beam of some succeeding system, provision has been made for re-entering the correlation matrix which appears as a triangular matrix in the beam output. (See section under type code 1.0 and/or the Appendix for definitions.)

There are 16 parameters:

1 - Type code 12.0

2 to 16 - The 15 correlations (r(ij)) among the 6 beam components - in the order printed (by rows).

Several cards may be used to insert the 15 correlations, if necessary.

Since this element is solely an extension of the beam input, a 12.0 element must immediately be preceded by a 1.0 (BEAM) element entry.

The effect of this element in the printed output is shown only in the beam matrix. If the beam matrix is printed automatically, it is not printed directly after the BEAM element but only after the correlation matrix has been inserted.

Output PRINT CONTROL instructions: Type code 13.0

A number of control codes which transmit output print instructions to the program have been consolidated into a single type code:

There are two parameters:

1 - Type code 13.0

2 - Code number.

The effects of the various code numbers will be described below (not in numerical order).

Several codes are available to control various aspects of the printed output. Most type codes produce a line of output that advertises their existence. Those that do not, usually have an obvious effect upon the remainder of the output and thus make their presence clear.

Beam matrix print controls 1., 2., 3.

(13. 1. ;): The current beam (σ) matrix is printed by this code.

(13. 3. ;): The beam (σ) matrix will be printed after every physical element which follows this code.

(13. 2. ;): The effect of a previous (13. 3. ;) code is cancelled and the beam (σ) matrix is printed only when a (13. 1. ;) code is encountered or when another (13. 3. ;) code is inserted. The suppression of the beam matrix is the normal default.

Transformation matrix print controls 4., 5., 6., 24.

(13. 4. ;): The current transformation matrix R1 (TRANSFORM 1) is printed by this code. If the program is computing a second-order matrix, this second-order transformation matrix will be included in the print-out. This matrix is cumulative from the last R1 (TRANSFORM 1) update. The units of the elements of the printed matrix are consistent with the input units associated with the type code 1.0 (BEAM) entry.

(13. 6. ;): The transformation matrix R1 will be printed after every physical element which follows this code. The second-order matrix will be printed automatically only if the one-line form (code 13. 19. ;) of the transformation is selected. The second-order matrix will, however, be printed at each location of a (13. 4. ;) element. The first-order matrix will not be repeated.

(13. 5. ;): The automatic printing of R1 will be suppressed and R1 will be printed only when subsequently requested.

(13. 24. ;): The TRANSFORM 2 matrix, R2, will be printed by this code. The format and units of R2 are identical with those of R1, which is printed by the (13. 4. ;) code. For a list of elements which update the R2 matrix, see type code 6.

The units of the tabulated matrix elements in either the first-order R or sigma matrix or second-order T matrix of a TRANSPORT print-out will correspond to the units chosen for the BEAM card. For example, the R(12) = (x/θ) matrix element will normally have the dimensions of cm/mr; and the T(236) = $(\theta/y\delta)$ matrix element will have the dimensions mr/(cm-percent $\Delta p/p$) and so forth.

Misalignment table print control 8.

The misalignment summary table is printed wherever a (13. 8. ;) element is inserted. Its contents are the effects of all previously specified misalignments whose results were to be stored in a table. A full description of the table and its contents is to be found in the section on the align element (type code 8.).

Coordinate layout control 12.

One can produce a layout of a beam line in any Cartesian coordinate system one chooses. The coordinates printed represent the x, y, and z position, and the angles theta, phi, and psi, respectively, of the reference trajectory at the interface between two elements. Theta is the angle which the floor projection of the reference trajectory makes with the floor z axis. Phi is the vertical pitch. Psi is a rotation about the reference trajectory. In the printed output the values given are those at the exit of the element listed above and at the entrance of the element listed immediately below.

A request for a layout is specified by placing a (13. 12. ;) card before the beam card. If no additional cards are inserted the reference trajectory of the beam line will be assumed to start at the origin and proceed along the positive z-axis. The y-axis will point up and the x-axis to the left. One can also specify other starting coordinates and orientations by placing certain other cards before the beam card. For a description of such cards see type code 16.0 (special parameters).

The calculation of the coordinates is done from the parameters of the physical elements as given in the data. Therefore, if effective lengths are given for magnetic elements, the coordinates printed will be those at the effective field boundary. The effects of fringing fields in bending magnets are not taken into account.

General output format controls 17., 18., 19.

(13. 17. ;): The subsequent printing of the physical parameters of all physical elements will be suppressed. Only the type code and the label will remain. This element is useful in conjunction with the (13. 19. ;) element which restricts the beam (σ) matrix and the transformation (R) matrix each to a single row. The elements of these matrices then appear in uninterrupted columns in the output, similar to the TRAMP computer code used at the Rutherford Lab, CERN, and elsewhere.

(13. 18. ;): Only varied elements and constraints will be printed. This element, in conjunction with the various options on the indicator card, can produce a very abbreviated output. The entire output of a multistep problem can now easily be printed on a teletype or other terminal.

(13. 19. ;): The beam (σ) and transformation (R1 or R2) matrices, when printed, will occupy a single line. Only those elements are printed which will be non-zero if horizontal midplane symmetry is maintained. The second-order transformation matrix will obviously occupy several lines. This element, in conjunction with the 13. 17. ; element and either the 13. 3. ; element or the 13. 6. ; element, will produce output in which the printed matrix elements will occupy single uninterrupted columns. For visual appearances it is recommended that, if both beam (σ) and transformation matrices are desired, they be printed in separate steps of a given problem.

Punched output controls 29., 30., 31., 32., 33., 34., 35., 36.

If the control is equal to 29, all of the terms in the first-order matrix and the x and y terms of the second-order matrix are punched.

If the control is equal to 30, all of the terms of the first-order matrix and all second-order matrix elements are punched out.

If the control, n, is greater than 30, all of the first-order terms are punched and the second-order matrix elements which correspond to (n-30.), i.e. if n = 32, the second-order theta matrix elements are punched out. If n = 31, the second-order x matrix elements are punched, and so forth.

ARBITRARY TRANSFORMATION input: Type code 14.0

To allow for the use of empirically determined fringing fields and other specific (perhaps non-phase-space-conserving) transformations, provision has been made for reading in an arbitrary transformation matrix. The first-order 6 × 6 matrix is read in row by row.

There are eight parameters for each row of a first-order matrix entry:

1 - Type code 14.0

2 to 7 - The six numbers comprising the row. The units must be those used to print the transfer matrix; in other words, consistent with the BEAM input/output.

8 - Row number (1. to 6.)

A complete matrix must be read and applied one row at a time. Rows that do not differ from the unit transformation need not be read.

For example, (14. -.1 .9 0. 0. 0. 0. 2. ;) introduces a transformation matrix whose second row is given but which is otherwise a unit matrix. Note that this transformation does not conserve phase space because $R(22) = 0.9$, i.e. the determinant of $R \neq 1$.

Any of the components of a row may be varied; however, there are several restrictions.

Type code 14.0 elements that immediately follow one another will all be used to form a single transformation matrix. If distinct matrices are desired, another element must be inserted to separate the type code 14.0 cards. Several do-nothing elements are available; for example, a zero length drift (3. 0. ;) is a convenient one.

When the last of a sequence of type code 14.0 cards is read, the assembled transformation matrix will be printed in the output.

Note that

$$\begin{pmatrix} 1 & 0 \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} a_{11} & a_{12} \\ 0 & 1 \end{pmatrix} \neq \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$

Hence, a matrix formed by successive 14. (3. 0. ;), 14. - elements is not always equal to the one formed by leaving out the (3. 0. ;) element.

If components of a 14.0 card are to be varied it must be the last 14.0 card in its matrix. This will force a matrix to be split into factors if more than one row has variable components.

If it is desired to read in the second-order matrix coefficients for the i^{th} row, then the following 22 additional numbers may be read in**).

9 - continuation code 0.

10 to 30 - the 21 coefficients:

T(i11) T(i12) T(i13) T(i14) T(i15) T(i16)
T(i22) T(i23) T(i24) T(i25) T(i26) T(i33)
T(i34) T(i35) T(i36) T(i44) T(i45) T(i46)
T(i55) T(i56) T(i66)

in that order, where i is the row number. It is necessary to read in the first-order matrix row which corresponds to the second-order matrix row being read in.

As in the first-order case, full rows not different from the identity matrix [i.e., R(ii) = 1, all other R(ij) = 0, and all T(ijk) = 0] need not be read in.

**) This feature frees the user from making repetitive, expensive, second-order runs through a fixed portion of his system while experimenting with other magnets. This is done by reading the full matrix of this portion (obtained from a previous run) back into the machine as a single "arbitrary matrix."

Input-output UNITS: Type code 15.0

TRANSPORT is designed with a standard set of units that have been used throughout this manual. However, to accommodate other units conveniently, provision has been made for redefining the units to be employed. This is accomplished by insertion of one or more of the following elements.

There are four parameters to be specified:

1 - Type code 15.0

2 - Code digit.

3 - The abbreviation of the unit (see examples below).
This will be printed on the output listing. It must be enclosed in single quotes and is a maximum of three characters long (four for energy). The format for insertion is the same as for labels.

4 - The scale factor (if needed).
The scale factor is the size of the new unit relative to the standard TRANSPORT unit. For example, if the new unit is inches and the standard TRANSPORT unit cm, the scale factor is (2.54).

The various units that may be changed are:

Code Digit	Quantity	Standard TRANSPORT Unit	Symbols used in SLAC-75
1.0	horizontal and vertical transverse dimensions, magnet apertures and mis-alignment displacements.	cm	x,y
2.0	horizontal and vertical angles and misalignment rotation angles	mr	θ,ϕ
3.0	vertical beam extent (only)*) and bending magnet gap height	cm	y
4.0	vertical beam divergence*) (only)	mr	ϕ
5.0	pulsed beam length and wave length in accelerator	cm	ℓ
6.0	momentum spread	percent (PC)	δ
7.0	bend, pole face rotation, and coordinate layout angles	degrees (DEG)	
8.0	length (longitudinal) of elements, layout co-ordinates and bending magnet pole face curvatures	metres (M)	t
9.0	magnetic fields	kG	B
10.0	mass	electron mass	m
11.0	momentum and energy gain in accelerator section	GeV/c GeV	p(0) ΔE

*) These codes should not be used if the coordinate rotation (20.0) type code is used anywhere in the system.

Units are not normally restored at the end of a problem step. Once changed, they remain the same for all succeeding problem steps in an input deck until a 0 indicator card is encountered, at which time they are reset to standard TRANSPORT units. The units may be reset to standard units by inserting a (15. ;) type code entry.

The 15.0 elements are the first cards in a deck (immediately following the title card and the 0 or 1 indicator card) and should not be inserted in any other location. They produce no printed output during the calculation, their effect being visible only in the output from other elements.

Example: To change length to feet, width to inches, and momentum to MeV/c, add to the front of the deck the elements

```
15.  8.  ' FT'  0.3048;
15.  1.  ' IN'  2.54;
15. 11.  'MEV'  0.001;
```

The scale factor, 0.3048, multiplies a length expressed in the new unit, feet, to convert it to the reference unit, metres, etc.

For the conventional units listed below, it is sufficient to stop with the unit name (the conversion factor is automatically inserted by the program). If units other than those listed below are desired, then the unit name and the appropriate conversion factor must be included. If the automatic feature is used with older versions of the program, there must be no blank spaces between the quotes and the unit name.

Input-output units: Type code 15.0

(Conversion factors for dimension changes versus code digit and label)

LABEL	CODE DIGIT										
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
'CM'	1.	---	1.	---	1.	---	---	.01	---	---	---
'M'	100.	---	100.	---	100.	---	---	1.	---	---	---
'IN'	2.54	---	2.54	---	2.54	---	---	.0254	---	---	---
'FT'	30.48	---	30.48	---	30.48	---	---	.3048	---	---	---
'MM'	.1	---	.1	---	.1	---	---	.001	---	---	---
'R'	---	1000.	---	1000.	---	---	---	---	---	---	---
'MR'	---	1.	---	1.	---	---	---	---	---	---	---
'PC'	---	---	---	---	---	1.	---	---	---	---	---
'P/10'	---	---	---	---	---	.1	---	---	---	---	---
'N'	---	---	---	---	---	100.	---	---	---	---	---
'MEV'	---	---	---	---	---	---	---	---	---	---	.001
'GEV'	---	---	---	---	---	---	---	---	---	---	1.
'KG'	---	---	---	---	---	---	---	---	1.	---	---
'G'	---	---	---	---	---	---	---	---	.001	---	---

PC is an abbreviation for percent
P/10 means one-tenth of a percent
N means 100 percent

SPECIAL INPUT PARAMETERS: Type code 16.0

A number of constants are used by the program which do not appear as parameters in elements of any other type code. A special element has been provided to allow the designer to set their values. These special parameter entries must always precede the physical element(s) to which they apply. Once introduced, they apply to all succeeding elements in the beam line unless reset to zero or to new values.

There are three parameters:

1 - Type code 16.0

2 - Code digit.

3 - Value of the constant.

A number of such constants have been defined in this manner. All have a normal value that is initialized at the beginning of each run.

Code digits for special parameters

1. $\varepsilon(1)$ - a second-order measure of magnetic field inhomogeneity in bending magnets. If

$$B(x) = B(0)\left[1 - n\left(\frac{x}{\rho_0}\right) + \beta\left(\frac{x}{\rho_0}\right)^2 - \ldots\right]$$

is the field expansion in the median ($y = 0$) plane, then $\varepsilon(1)$ is defined as

$$\varepsilon(1) = \beta\left(\frac{1}{\rho_0}\right)^2$$

(where ρ_0 is measured in units of horizontal beam width - normally cm). This parameter affects second-order calculations only. Normally the value if 0. It may be varied in second-order fitting.

3. (M/m) - Mass of the particles comprising the beam, in units of the electron mass; normally 0. A non-zero mass introduces the dependence of pulse length on velocity, an important effect in low-energy pulsed beams.

4. W/2 - Horizontal half-aperture of bending magnet, in the same units as horizontal beam width, normally 0 (i.e. effect of horizontal half aperture is ignored).

5. g/2 - Vertical half-aperture of bending magnet, in the same units as vertical beam height; this parameter must be inserted if the effect of the spatial extent of the fringing fields upon transverse focusing is to be taken into account. (See type codes 2.0 and 4.0 as a cross reference) normally 0.

6. L - Cumulative length of system, in the same units as system length. It is set to zero initially, then increased by the length of each element, and finally printed at the end of the system. This element allows the cumulative length to be reset as desired.

7. K_1 - An integral related to the extent of the fringing field of a bending magnet. See section under type code 2.0 and SLAC-75 page 74 for further explanation.
If the (16. 5. g/2. ;) element has been inserted, the program inserts a default value of $K_1 = \frac{1}{2}$ unless a (16. 7. K_1. ;) element is introduced, in which case the program uses the K_1 value selected by the user. The table below shows typical values for various types of magnet designs.

8. K_2 - A second integral related to the extent of the fringing field. Default value of $K_2 = 0$ unless specified by a (16. 8. K_2. ;) entry.

Typical values of K_1 and K_2 are given below for four types of fringing field boundaries:

a) a linear drop-off of the field,

b) a clamped "Rogowski" fringing field,

c) an unclamped "Rogowski" fringing field,

d) a "square-edged" <u>non-saturating</u> magnet

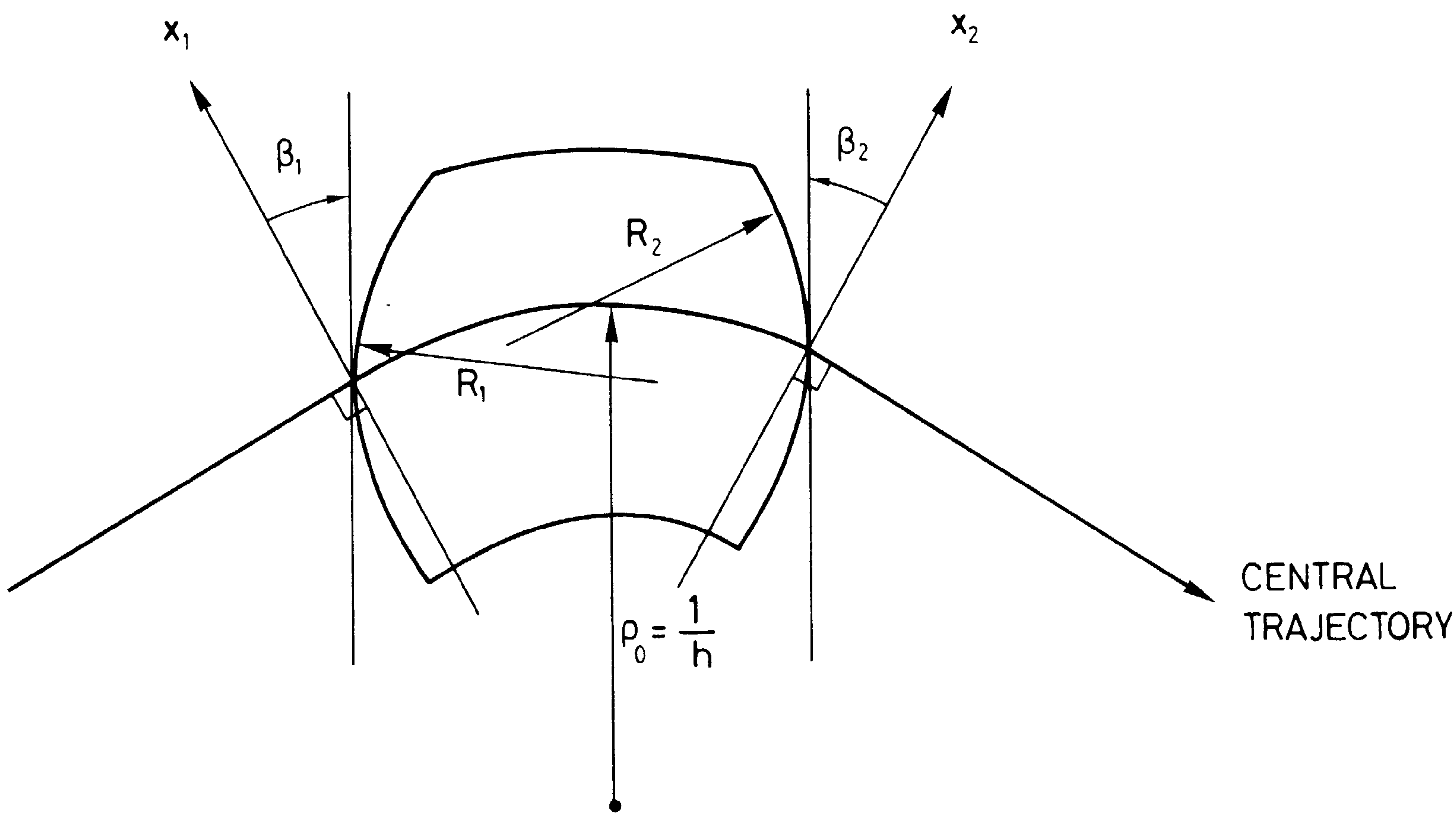
Model	K_1	K_2 *)
Linear	1/6	3.8
Clamped Rogowski	0.4	4.4
Unclamped Rogowski	0.7	4.4
Square-edged magnet	0.45	2.8

12. $1/R_1$ - Where R_1 is the radius of curvature (in units of longitudinal length, normally metres) of the entrance face of bending magnets. (See figure on p.

13. $1/R_2$ - Where R_2 is the radius of curvature (in units of longitudinal length, normally metres) of the exit face of bending magnets. (See figure on p.

The pole face curvatures $(1/R_1)$ and $(1/R_2)$ affect the system only in second-order, creating an effective sextupole component in the neighbourhood of the magnet. If the parameters are not specified, they are assumed to be zero, i.e. no curvature and hence no sextupole component. Either parameter (or both) may be varied in second-order fitting.

*) For most applications K_2 is unimportant. If you find it is important to your result you should probably be making a more accurate calculation with a ray-tracing program (see References at the end of the manual.)



FIELD BOUNDARIES FOR BENDING MAGNETS

The TRANSPORT sign conventions for x, β, R and h are all positive as shown in the figure. The positive y direction is out of the paper. Positive β's imply transverse focusing. Positive R's (convex curvatures) represent negative sextupole components of strength $S = (-\ h/2R)\ \sec^3 \beta$. (See SLAC-75, page 71.)

Tilt-to-focal plane (16. 15. α. ;) element

Very often it is desired to have a listing of the second-order aberrations along the focal plane of a system rather than perpendicular to the optic axis, i.e. along the x coordinate. If the focal plane makes an angle α with respect to the x axis (measured clockwise) then provision has been made to rotate to this focal plane and print out the second-order aberrations. This is achieved by the following procedures:

Alpha is the focal-plane tilt angle (in degrees) measured from the perpendicular to the optic axis (α is normally zero).

The programming procedure for a tilt in the x(bend)-plane (rotation about y axis) is:

```
16.  15.  α.  ;
 3.   0.  ;   (a necessary do-nothing element)
13.   4.  ;
16.  15.  -α.  ;  (rotate back to zero)
 3.   0.  ;   (a necessary do-nothing element)
16.  15.  0.  ; (to turn off rotation element)
```

The programming procedure for a tilt in the y-plane (rotation about x-axis) is:

```
16.  15.  α.  ;
20.  90.  ;
 3.   0.  ;
20. -90.  ;
13.   4.  ;
16.  15.  -α.  ;  (rotate back to zero)
 3.   0.  ;
16.  15.  0.  ;  (to turn off rotation element)
```

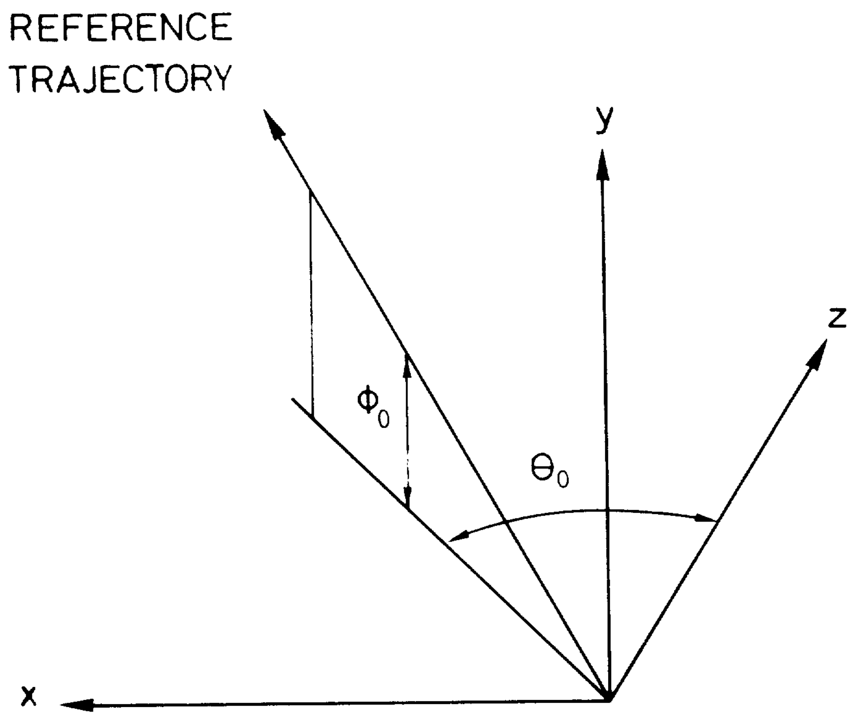
Initial beam line coordinates and direction

When requesting a beam line coordinate layout via a (13. 12. ;) element one can employ any coordinate system one desires. The position and direction of the beginning of the reference trajectory in this coordinate system are given on elements 16. 16. through 16. 20. Such cards should be placed before the beam card, but after any units changes. Their meanings are as follows:

16.	16.	x_0, y_0, and z_0, respectively, the coordinates of
16.	17.	the initial point of the reference trajectory
16.	18.	in the units chosen for longitudinal length.
16.	19.	θ_0 and ϕ_0 the initial horizontal and vertical angles
16.	20.	of the reference trajectory in degrees.

When specifying the initial orientation of the reference trajectory via the two angles, one must give the horizontal angle first. The meaning of the two angles is given in the following figure. Any of the above five parameters not explicitly specified will be taken to equal zero.

The initial coordinates may be varied in first-order fitting. Their values will affect only the beam line floor coordinates and not any beam or transfer matrix element.



SPECIFICATION OF INITIAL ANGLES θ_0 AND ϕ_0 FOR BEAM LINE LAYOUT.

SECOND-ORDER CALCULATION: Type code 17.0

A second-order calculation may be obtained provided no alignments are employed. A special element instructs the program to calculate the second-order matrix elements. It must be inserted immediately following the beam (1. element).

Only one parameter should be specified:

1 - Type code 17.0 (signifying a second-order calculation is to be made).

To print out the second order T1 matrix terms at a given location in the system, the (13. 4. ;) print control card is used. For T2, the (13. 24. ;) print control card is used. The update rules are the same as those for the corresponding first-order R matrix. See SLAC-75 for definitions of subscripts in the second order T(ijk) matrix elements.

The values of the BEAM (sigma) matrix components may be perturbed from their first-order value by the second-order aberrations. In a second-order TRANSPORT calculation, the initial beam is assumed to have a Gaussian distribution. For exact details the reader should consult the Appendix. For the beam matrix to be calculated correctly, there should be no elements which update the R2 matrix. If a centroid shift is present, it must immediately follow the beam (type code 1.0) or beam rotated ellipse (type code 12.0) card.

Only second-order fitting may be done in a second-order run. See the section on type code 10.0 for a list of quantities that may be constrained in a second-order run. If a beam constraint is to be imposed in second-order, there must be no centroid shifts present anywhere.

Second-order matrices are included in the program for quadrupoles, bending magnets (including fringing fields), the arbitrary matrix, sextupoles, and solenoids. They have not been calculated for the acceleration (type code 11.0) element.

SEXTUPOLE: Type code 18.0

Sextupole (hexapole) magnets are used to modify second-order aberrations in beam transport systems. The action of a sextupole on beam particles is a second and higher order effect, so in first order runs (absence of the 17.0 card) this element will act as a drift space.

There are four parameters:

1 - Type code 18.0
2 - Effective length (metres).
3 - Field at pole tips (kG). Both positive and negative fields are possible (see figures below).
4 - Half-aperture (cm). Radius of circle tangent to pole tips.

Other orientations of the sextupole may be obtained using the beam rotation element (type code 20.0).

The pole tip field may be varied in second-order fitting. It may also be constrained not to exceed a certain specified maximum field. (See the explanation of vary codes in the section on type code 10.0). Such a constraint allows one to take into account the physical realities of limitations on pole tip fields.

See SLAC-75 for a tabulation of sextupole matrix elements. The TRANSPORT input format for a typical data set is:

```
                  ┌── Label if desired (not to exceed
18. L. b. a. ' '  ;                       4 spaces)
```

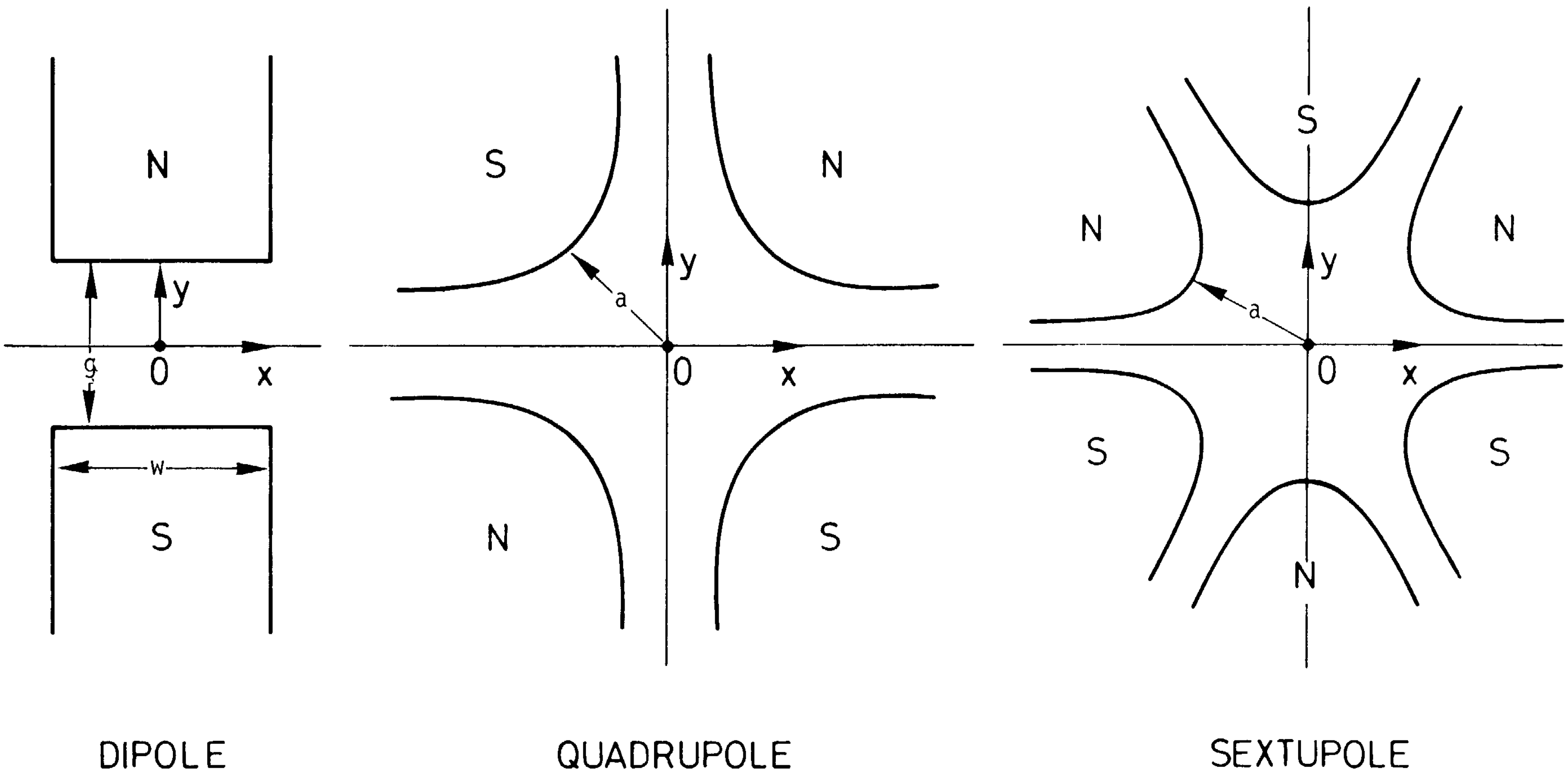


ILLUSTRATION OF THE MAGNETIC MIDPLANE (x AXIS) FOR DIPOLE, QUADRUPOLE AND SEXTUPOLE ELEMENTS. THE MAGNET POLARITIES INDICATE MULTIPOLE ELEMENTS THAT ARE POSITIVE WITH RESPECT TO EACH OTHER.

SOLENOID: Type code 19.0

The solenoid is most often used as a focusing element in systems passing low-energy particles. Particles in a solenoidal field travel along helical trajectories. The solenoid fringing field effects necessary to produce the focusing are included.

There are three parameters:

1 - Type code 19.0
2 - Effective length of the solenoid (metres).
3 - The field (kG). A positive field, by convention, points in the direction of positive z for positively charged particles.

The length and the field may be varied in first-order fitting. Both first- and second-order matrix calculations are available for the solenoid.

A typical input format is:

```
                  ┌──── Label if desired (not to exceed
                  ↓                          4 spaces)
19.  L.  B.  ' '  ;
```

First-order solenoid matrix

Solenoid R matrix

Definitions: L = effective length of solenoid

K = $B(0)/(2B\rho_0)$, where B(0) is the field inside the solenoid and $(B\rho_0)$ is the (momentum) of the central trajectory.

C = cos KL

S = sin KL

For a derivation of this tranformation see report SLAC-4 by R. Helm.

Alternate forms of matrix representation of the solenoid:

$$R(\text{Solenoid}) = \begin{bmatrix} C^2 & \frac{1}{K}SC & SC & \frac{1}{K}S^2 & 0 & 0 \\ -KSC & C^2 & -KS^2 & SC & 0 & 0 \\ -SC & -\frac{1}{K}S^2 & C^2 & \frac{1}{K}SC & 0 & 0 \\ KS^2 & -SC & -KSC & C^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Rotating the transverse coordinates about the z axis by an angle = -KL decouples the x and y first-order terms, i.e.

$$R(-KL) \cdot R(\text{Solenoid}) = \begin{pmatrix} C & \frac{1}{K}S & 0 & 0 & 0 & 0 \\ -KS & C & 0 & 0 & 0 & 0 \\ 0 & 0 & C & \frac{1}{K}S & 0 & 0 \\ 0 & 0 & -KS & C & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

COORDINATE ROTATION: Type code 20.0

The transverse coordinates x and y may be rotated through an angle α about the z axis (the axis tangent to the central trajectory at the point in question)**). Thus a rotated bending magnet, quadrupole, or sextupole may be inserted into a beam transport system by preceding and following the element with the appropriate coordinate rotation. (See examples below.) The positive sense of rotation is clockwise about the positive z axis.

There are two parameters to be specified for a coordinate rotation:

1 - Type code 20.0 (signifying a beam coordinate rotation).
2 - The angle of rotation α (degrees).

The angle of rotation may be varied in a first-order fitting (see type code 10.0).

Note

This transformation assumes that the units of (x and y) and (θ and ϕ) are the same. This is always true unless a 15.0 3.0 or a 15.0 4.0 type code has been used.

**) See SLAC-75[4], page 45 and Fig. 4, page 12 for definitions of x, y, and z coordinates.

Examples:

For a bending magnet, the beam rotation matrix may be used to specify a rotated magnet.

Example No. 1

A bend up is represented by rotating the x, y coordinates by -90.0 degrees as follows:

```
                 ┌──── Labels (not to exceed 4 spaces) if desired
                 ↓
20.  -90.    '  '  ;
2.   β(1).   '  '  ;
4.   L.  B.  n.  '  '  ;
2.   β(2).   '  '  ;
20.  +90.    '  '  ;  (returns coordinates to their initial
                        orientation)
```

A bend down is accomplished via a +90 degree rotation.

```
20.  +90.   '  '  ;
2.
4.
2.
20.  -90.   '  '  ;
```

A bend to the left (looking in the direction of beam travel) is accomplished by rotating the x, y coordinates by 180 degrees, e.g.

```
20.  180.   '  '  ;
2.
4.
2.
20.  -180.  '  '  ;
```

Example No. 2

A quadrupole rotated clockwise by 60 degrees about the positive z axis would be specified as follows:

```
20.  60.  ' '  ;
5.  L.  B.  a.  ' '  ;
20.  -60.  ' '  ;
```

Beam rotation matrix

$$R = \begin{pmatrix} C & & S & & & \\ & C & & S & & \\ -S & & C & & & \\ & -S & & C & & \\ & & & & 1 & \\ & & & & & 1 \end{pmatrix}$$

where $C = \cos \alpha$,

$S = \sin \alpha$,

α = angle of coordinate rotation about the beam axis,

blank spaces are zeros.

e.g. for α = +90 degrees, this matrix interchanges rows 1 and 2 with 3 and 4 of the accumulated R matrix as follows:

$$\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} R(11) & R(12) & R(13) & R(14) \\ R(21) & R(22) & R(23) & R(24) \\ R(31) & R(32) & R(33) & R(34) \\ R(41) & R(42) & R(43) & R(44) \end{bmatrix} \begin{bmatrix} R(31) & R(32) & R(33) & R(34) \\ R(41) & R(42) & R(43) & R(44) \\ -R(11) & -R(12) & -R(13) & -R(14) \\ -R(21) & -R(22) & -R(23) & -R(24) \end{bmatrix}$$

(The rest of the matrix is unchanged.)

STRAY MAGNETIC FIELD: Type code 21.0

1 - Element No. 21.0

2 - Code No. n. n = 4: horizontal deflection

n = 2: vertical deflection.

3 - $<\overline{BL}>$ mean value of $\int Bdz$.

4 - ± $<\sigma BL>$ +: Gaussian random number generator; affects beam first moment.

-: uncertainty in $\int Bdz$ - affects beam second moment.

Uses the misalignment element (8.) to calculate an angular deflection equal to $\int \frac{Bdz}{(B\rho)}$

This type code is not functioning in the present version of the program.

SENTINEL

Each step of every problem in a TRANSPORT data set must be terminated with the word SENTINEL. The word SENTINEL need not be on a separate card. For a description of the form of a TRANSPORT data set see the section on input format.

An entire run, consisting of one or several problems, is indicated by an additional card containing the word SENTINEL. Thus, at the end of the entire data set the word SENTINEL will appear twice.

Acknowledgements

R. Helm's suggestions and criticisms at SLAC have been invaluable throughout the development of the program and the underlying theory. R. Pordes has ably assisted D. Carey at FNAL during the more recent developments of the program.

REFERENCES

1. E.D. Courant and H.S. Snyder, Theory of the Alternating Gradient Synchrotron, Ann. Phys. (NY) 3, 1-48 (1958).

2. S. Penner, Calculations of properties of magnetic deflection systems, Rev. Sci. Instrum. 32, 150-160 (1961).

3. K.L. Brown, R. Belbeoch, and P. Bounin, First- and second-order magnetic optics matrix equations for the midplane of uniform-field wedge magnets, Rev. Sci. Instrum. 35, 481-485 (1964).

4. K.L. Brown, A first- and second-order matrix theory for the design of beam transport systems and charged particle spectrometers, SLAC Report No. 75, or Advances Particle Phys. 1, 71-134 (1967).

5. K.L. Brown and S.K. Howry, TRANSPORT/360 a computer program for designing charged particle beam transport systems, SLAC Report No. 91 (1970). The present manual supersedes the above reference.

6. K.L. Brown, A systematic procedure for designing high resolving power beam transport systems or charged particle spectrometers, Proc. 3rd Int. Conf. on Magnet Technology, Hamburg, Germany, May 1970, p. 348, or SLAC-PUB-762 June 1970.

7. Suggested Ray-Tracing Programs to supplement TRANSPORT:

   David C. Carey, "TURTLE (Trace Unlimited Rays Through Lumped Elements)", Fermilab Report No. NAL-64 (1971). This is a computer program using TRANSPORT notation and designed to be run using the same data cards as for a previous TRANSPORT run.

   K.L. Brown and Ch. Iselin, "DECAY TURTLE (Trace Unlimited Rays Through Lumped Elements)", CERN Report 74-2 (1974). This is an extension of TURTLE to include particle decay calculations.

   H. Enge and S. Kowalski have developed a Ray-Tracing program using essentially the same terminology as TRANSPORT. Any experienced user of TRANSPORT should find it easy to adapt to the M.I.T. program.

8. K.G. Steffen, High-energy beam optics, Interscience Monographs and Texts in Physics and Astronomy, Vol. 17, John Wiley and Sons, New York (1965).

SUGGESTED BIBLIOGRAPHY

A.P. Banford, The transport of charged particle beams (E. and F.N. Spon Ltd., London, 1966).

K.G. Steffen, High-energy beam optics, Interscience Monographs and Texts in Physics and Astronomy, Vol. 17 (John Wiley and Sons, NY, 1965).