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The facility in TRANSPORT for calculating the effect on a particle beam of a magnet misalignment has been greatly expanded and revised. Up to sixty times as much information may now be obtained in a single run. Independent misalignments of many magnets may be simulated by the use of a single element. The bilinear effects of a misalignment are now calculated. A bilinear effect is one which affects the beam line focusing characteristics, but not the central ray, such as the effect of rotating a quadrupole about its axis.

This document represents a complete replacement for the misalignment element (type code 8.) section in the TRANSPORT manual. It contains the information needed for using the misalignment element, with all its possible options. The mathematical theory of misalignment calculations is described in a forthcoming revision of the appendix to the TRANSPORT manual.

MAGNET ALIGNMENT TOLERANCES: Type code 8.0

The first order effects of the misalignment of a magnet or group of magnets are a shift in the centroid of the beam and a change in the beam focusing characteristics. Two varieties of misalignment are commonly encountered: 1) the magnet is displaced and/or rotated by a known amount; or 2) the actual position of the magnet is uncertain within a given tolerance. TRANSPORT has the capability of simulating the misalignment of either single magnets or entire sections of a beam line. Any combination of the above alternatives may be simulated through the use of the "align" element. The results may be displayed in either the printed output of the beam (sigma) matrix or tabulated in a special misalignment table (described below).

There are eight parameters to be specified:

1 - Type code 8.0 (specifying a misalignment).

2 - The magnet displacement in the horizontal direction (cm).

3 - A rotation about the horizontal axis (mr).

4 - A displacement in the vertical direction (cm).

5 - A rotation about the vertical axis (mr).

6 - A displacement in the beam direction (cm).

7 - A rotation about the beam direction (mr).

8 - A three digit code number (defined below) specifying the type of misalignment.

The three displacements and three rotations comprise the six degrees of freedom of a rigid body and are used as the six misalignment coordinates. The coordinate system employed is that to which the beam is referred at the point it enters the magnet. For example, a rotation of a bending magnet about the beam direction (parameter 7 above) is referred to the direction of the beam where it enters the magnet. The units employed are the standard TRANSPORT units shown above, unless redefined by type code 15. entries. If the units are changed, the units of the misalignment displacements are those determined by the 15. 1. type code entry; the units for the misalignment rotations are those determined by the 15. 2. type code entry.

The misalignment of any physical element or section of a beam line may be simulated. Misaligned sections of a beam line may be nested. A beam line rotation (type code 20.) may be included in a misaligned section. Thus, for example, one can simulate the misalignment of magnets that bend vertically. The arbitrary matrix (type code 14.) may not be included in a misaligned section. A misalignment must never be included in a second order run (type code 17.).

A misalignment element may indicate that a single magnet or section of the beam line is to be misaligned, or it may indicate that all subsequent magnets of a given type (quadrupoles and/or bending magnets) are to be misaligned. The type of misalignment is specified in the three-digit code number, and the location of the type code 8. align element depends of the type of misalignment.

If a misalignment pertains to a single magnet or a single section of the beam line, then the misalignment element (type code 8.) must directly follow that magnet or section of the beam line. If a misalignment element indicates that all subsequent magnets of a given type are to be misaligned, it must precede the first of such magnets. Further description of the available types of misalignment is given in the table below.

The results of the misalignment may be displayed in either the beam (sigma) matrix or in a misalignment table. If the results are displayed in the beam (sigma) matrix, then that matrix is altered by the effects of the misalignment. The effects of additional misalignments cause further alterations, so that at any point along the beam line, the beam (sigma) matrix will contain the combined effects of all previous misalignments.

The misalignment table can be used to show independently the effect on the beam matrix of a misalignment in each degree of freedom of each misaligned magnet. Each new misalignment to be entered in the table creates a new set of six duplicates of the beam matrix. Printed for each duplicate beam matrix are the centroid displacement and the beam half width in each of the six beam coordinates. Each of the six matrices shows the combined result of the undisturbed beam matrix and the effect of the misalignment in a single coordinate of a single magnet or section of the beam line. In a single TRANSPORT run the results of misaligning up to ten magnets or sections of the beam line may be included in the misalignment table.

Further requests for entry in the misalignment table will be ignored. Examples of such a table and the input which generated it are shown below.

When the user specified that the actual position of the magnet(s) is uncertain within a given tolerance, the printout will show a change in the beam (sigma) matrix resulting from the effects of the misalignment(s). Thus if one wishes to determine the uncertainty in the beam centroid resulting from uncertainties in the positioning of the magnets, the initial beam dimensions should be set to zero, i.e. the beam card entry at the beginning of the system should appear as follows:

1. 0. 0. 0. 0. 0. 0. p(0). ;

If it is desired to know the effect of an uncertainty in position on the beam focusing characteristics, then a non-zero initial phase space must be specified. The printout will then show the envelope of all possible rays, including both the original beam and the effects of the misalignment.

If the misalignment is a known amount, it may affact the beam centroid as well as the beam dimensions. Therefore one should place on the BEAM card the actual dimensions of the beam entering the system. For a known misalignment, the program requires that the initial beam specified by type code 1 must be given a non-zero phase volume, to insure a correct printout.

An align element pertaining to a single magnet or section of the beam line updates the BEAM (sigma) matrix and the R2 matrix, but not the R1 matrix. A misalignment element which indicates misalignment of all subsequent magnets of a given type will update the BEAM (sigma) matrix and the R2 matrix before each bending magnet with fringe fields and after each misaligned magnet of any type.

The tolerances may be varied. Thus type-vary code 8.111111 permits any of the six parameters (2 through 7 above) to be adjusted to satisfy whatever BEAM constraints may follow. For fitting, a misalignment must pertain to a single magnet or single section of the beam line, and the results must be displayed in the beam (sigma) matrix. (See the section under type code 10. for a discussion of the use of vary codes.)

The meaning of the options for each digit of the three-digit code number is given in the following table.

A. The units position specifies the magnet(s) or section of the beam line to be misaligned.

CODE NUMBER	INTERPRETATION
XX0.	The single magnet (type code element) immediately preceding the align card is to be misaligned. A bending magnet with fringe fields should be misaligned using one of the options described below.
XX1.	The last R1 matrix update (the start of the beam line or a 6. 0. 1. ; type code entry) marks the beginning of the section to be misaligned. The misalignment element itself marks the end. The section is treated as a unit and misaligned as a whole. The misalignments of quadrupole triplets and other combinations involving more than two quadrupoles may be studied using this code digit.
XX2.	The last R2 matrix update (see type code 6. for a list of elements which update R2) marks the beginning of the misaligned section. The misalignment element marks the end. This option makes use of the fact that R2 matrix updates do not affect the R1 matrix. A bending magnet with fringing fields or pole face rotations (type code 2.) should be misaligned using this option. See examples 1 and 2 below for an illustration of this.

An array of quadrupoles provides another example of the use of this option. By successive application of align elements, the elements of a quadrupole triplet could be misaligned relative to each other, and then the triplet as a whole could be misaligned. See example 3 below for an illustration of this.

XX3. All subsequent bending magnets and quadrupoles are independently misaligned by the amount specified. This option is useful in conjunction with the tabular display of the misalignment results (see below). A bending magnet, with fringing fields included is treated as a single unit and misaligned accordingly.

XX4. All subsequent bending magnets, including fringing fields, are independently misaligned by the amount specified. See XX3 above for further comments.

XX5. All subsequent quadrupoles are independently misaligned by the amount specified. See example 4 below for an illustration of this. See XX3 above for further comments.

B. The tens position defines the mode of display of the results of the misalignment

X0X.	The beam matrix contains the results of the misalignment. The beam matrix is printed wherever a 13. 1. ; card is encountered. The beam matrix will then contain contributions from all previous misalignments.
X1X.	A table is used to store the results of misalignments. The effect of up to ten independently misaligned magnets may be shown in the table in a single run. The table is printed via a 13. 8. ; card, and may be compared with the undisturbed beam matrix (printed by a 13. 1. ; card) at any point. An example of such a table is shown below.

C. The hundreds position distinguishes between an uncertainty in position (0XX.) or a known displacement (1XX.).

Any combination of digits may be used to define the exact circumstances intended. Thus, code 111. indicates the deliberate displacement of a set of magnets (referred to the point where the beam enters the set), with the results to be stored in a table.

Example No. 1: A bending magnet with a known misalignment

A bending magnet (including fringe fields) misaligned by a known amount might be represented as follows:

```
3.   L(1).   ;
6.  0.  2.  ;
2.  0.  ;  4.  1.  B.  n.  ;  2.  0.  ;
8.  0.  0.  0.  0.  0.  2.  102.  ;
3.   L(2).   ;
```

This represents a known rotation of the bending magnet about the incoming beam direction (z axis) by 2.0 mr. The result of this misalignment will be a definite shift in the beam centroid, and a mixing of the horizontal and vertical coordinates. The use of the 6. 0. 2. ; transform 2 update and the misalignment code number XX2 is necessary because the magnetic array (bending magnet + fringing fields) consists of three type code elements instead of one.

Example No. 2: A bending magnet with an uncertain position

A bending magnet having an uncertainty of 2 mrad in its angular positioning about the incoming beam (z axis) would be represented as follows:

```
3.   L(1).   ;
6.  0.  2.  ;
2.  0.  ;  4.  L.  B.  n.  ;  2.  0.  ;
8.  0.  0.  0.  0.  0.  2.0  002.  ;
3.   L(2).  ;
```

To observe the uncertainty in the location of the outcoming beam centroid, the input BEAM card should have zero phase space dimensions as follows:

```
1.   0.   0.   0.   0.   0.   0.   p(0).   ;
```

If the beam dimensions on the input BEAM card are non-zero, the resultant beam (sigma) matrix will show the envelope of possible rays, including both the input beam and the effect of the misalignment.

Example No. 3: A misaligned quadrupole triplet

One typical use of both the R1 and R2 matrices is to permit the misalignment of a triplet. For example, an uncertainty in the positions within the following triplet:

```
5.   1.   -8.   10.   ;
5.   2.    7.   10.   ;
5.   1.   -8.   10.   ;
```

may be induced by appropriate 8. elements as noted:

```
6.   0.    1.   ;
5.   1.   -8.   10.   ;
6.   0.    2.   ;
5.   2.    7.   10.   ;
5.   1.   -8.   10.   ;
8.   ---   ---   ---   ---   ---   ---   000.   ;
8.   ---   ---   ---   ---   ---   ---   002.   ;
8.   ---   ---   ---   ---   ---   ---   001.   ;
```

The first 8. card in the list refers to the misalignment of the third magnet only. The second 8. card refers to the misalignment of the second and third magnets as a single unit via the R2 matrix update (the 6. 0. 2. ; entry). The last 8. card refers to the misalignment of the whole triplet as a single unit via the R1 matrix update (the 6. 0. 1. ; entry).

The comments about the BEAM card (type code 1. entry) in example 2 above are applicable here also.

Example No. 4: Misaligned quadrupoles in a triplet

Individual uncertainties in the positions of the quadrupoles in the triplet in example no. 3 above may be induced by a single misalignment card as follows:

8.	---	---	---	---	---	---	015.	;
5.	1.	-8.	10.	;				
5.	2.	7.	10.	;				
5.	1.	-8.	10.	;				

The effect of each misalignment coordinate on each quadrupole will be stored separately in a table. This table is printed wherever a 13. 8. ; type code is inserted.

```
'RECOMBINED MODE OF HIGH RESOLUTION BEAM N 6'
 0
15.      7.      'MR'
15.      8.      ' FT'      .3048
16.      19.     2.5
8.0      0.02    0.1        0.02     0.1      0.1     1.0     015
1.0      0.05    0.562      0.05     0.867    0.0     1.0     200.0
3.0      80.75
20.      180.
4.0      10.25   9.18192    'B1'
20.      -180.
3.0      1.75
20.      180.
4.       10.25   9.18192    'B2'
20.      -180.
3.       27.69
5.       10.0    -4.0006    2.54     'Q1'
3.       7.7
13.      1.
13.      4.      'C2A'
3.       3.6
5.0      10.0    3.4551     2.54     'Q2'
3.       5.
13.      1.
13.      4.      'C2B'
3.       1.5
20.      180.
2.       8.53
4.       20.     18.67      'B3'
2.       8.53
20.      -180.
3.0      1.50
20.      180.
2.       8.53
4.0      20.0    18.67      'B4'
2.       8.53
20.      -180.
3.0      1.50
20.      180.
2.       8.53
4.0      20.0    18.67      'B5'
2.       8.53
20.      -180.
13.      1.
13.      4.
3.       5.5
5.0      10.0    3.5176     2.54     'Q3'
3.0      2.0
5.0      10.0    -3.6476    2.54     'Q4'
3.0      289.84
13.      1.
13.      8.
13.      4.      'C3'
```

misalignment element

quadrupoles to be misaligned

print instruction for misalignment table

more beam line including more quadrupoles and misalignment table print instructions

```
SENTINEL
```

Input for a Misalignment Table

Shown is the input for a misalignment run of the early part of a beam line. The misalignment element specifies that all subsequent quadrupoles are to be given an uncertain misalignment by the amount specified and the results (for up to ten quadrupoles) are to be entered in a table. The portion of the output produced by the indicated print instruction is shown in the next figure.

0.0	0.086 CM					
0.0	0.329 MR	0.035				
0.0	0.168 CM	-0.000	0.000			
0.0	0.338 MR	0.000	0.000	-0.648		
0.0	0.209 CM	-0.010	-1.000	-0.000	0.000	
0.0	0.0 PC	0.0	0.0	0.0	0.0	0.0

LE FOR MISALIGNMENTS OF

0.100 MR		0.020 CM		0.100 MR		0.100 CM		1.000 MR	
0.0	0.087 CM	0.0	0.087 CM	0.0	0.121 CM	0.0	0.087 CM	0.0	0.094 CM
0.0	0.329 MR	0.0	0.325 MR	0.0	0.330 MR	0.0	0.329 MR	0.0	0.329 MR
0.0	0.200 CM	0.0	0.221 CM	0.0	0.167 CM	0.0	0.167 CM	0.0	0.172 CM
0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR
0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM
0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC
0.0	0.086 CM	0.0	0.086 CM	0.0	0.138 CM	0.0	0.086 CM	0.0	0.094 CM
0.0	0.329 MR	0.0	0.329 MR	0.0	0.330 MR	0.0	0.329 MR	0.0	0.329 MR
0.0	0.192 CM	0.0	0.192 CM	0.0	0.168 CM	0.0	0.168 CM	0.0	0.172 CM
0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR
0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM
0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC
0.0	0.086 CM	0.0	0.086 CM	0.0	0.136 CM	0.0	0.086 CM	0.0	0.094 CM
0.0	0.329 MR	0.0	0.329 MR	0.0	0.330 MR	0.0	0.329 MR	0.0	0.329 MR
0.0	0.183 CM	0.0	0.193 CM	0.0	0.168 CM	0.0	0.168 CM	0.0	0.172 CM
0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR
0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM
0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC
0.0	0.086 CM	0.0	0.086 CM	0.0	0.125 CM	0.0	0.086 CM	0.0	0.094 CM
0.0	0.329 MR	0.0	0.329 MR	0.0	0.330 MR	0.0	0.329 MR	0.0	0.329 MR
0.0	0.190 CM	0.0	0.703 CM	0.0	0.168 CM	0.0	0.168 CM	0.0	0.172 CM
0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR	0.0	0.338 MR
0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM	0.0	0.209 CM
0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC	0.0	0.0 PC

3 *

.00121	-0.00000	-0.00000	0.0	-6.33738
59566	-0.00000	-0.00000	0.0	-0.59994
.00000	-2.49643	0.13069	0.0	0.00000
.00000	-0.21783	-0.38916	0.0	0.00000
.37123	-0.00000	-0.00000	1.00000	-0.02757
.0	0.0	0.0	0.0	1.00000

Example of a Misalignment Table. The misalignment table, the unperturbed complete beam matrix, and the first-order transfer matrix are all shown at the same point in the beam line. The misalignment element (not shown) has indicated an uncertain misalignment, so the beam centroid is unaffected. The magnitudes of the misalignments in each coordinate are shown above the columns to which they pertain. The results of independently misaligning each magnet are indicated by the label for that magnet.