

LA-UR-11-00872

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<i>Title:</i>	Magnetic Field Tracking Features in MCNP6
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<i>Intended for:</i>	MCNP documentation and release



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Magnetic Field Tracking Features in MCNP6

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Introduction

Two methods for tracking charged particles in magnetic fields have been implemented in MCNP6. The first method utilizes transfer maps produced by COSY INFINITY, a separate beam optics code, and the second method uses direct ray-tracing techniques. In addition, for the ray tracing method, MCNP6 includes an option that simulates third-order aberrations for quadrupole magnets caused by fringe field effects by providing edge kicks for particles entering and exiting the magnet faces. This latter feature is especially important for proper particle transport through proton radiography beam lines and magnetic lenses.

This memo describes the two methods for magnetic field tracking and the new input card needed to implement them. Additional documentation on these methods, including V & V discussions, can be found in "Magnetic field tracking with MCNP5", LA-UR-04-2125.¹

Known problems and limitations

- Magnetic field tracking is only implemented for non-MCNPX mode ($dbcn(29) = 0$).
- COSY maps can only be applied to void cells.
- COSY maps are specific to particle momentum. Thus a particle with significantly different energy or mass than what was used to create the map will not be transported correctly.
- The ray tracing method is only implemented for constant and quadrupole magnetic fields
- Secondary particles produced along the track of the electron (knock-on electrons, k-xrays, and bremsstrahlung photons), and not created in the correct place, and could be in different cells, resulting in lost particles.
- Magnetic field tracking in lattices and multi-level universes is not implemented. However, the code does not check for this condition, and no warning messages are issued.
- No information about the magnetic fields is written to the output file.

Magnetic Field Tracking Methods

Transfer Maps

Several years ago, a patch² to MCNP and MCNPX was developed to transport charged particles using magnetic field transfer maps generated by the COSY INFINITY³ code, developed at the University of Michigan. This patch has been updated and inserted into MCNP6.

COSY INFINITY is a beam optics code that utilizes numerical integration and differential algebraic techniques to generate transfer maps based on a Taylor series expansion of a particle's canonical variables. These transfer maps represent the functional relation between the phase-space coordinates of a particle that has passed through a region of magnetic field and its phase-space coordinates before entering the field region. In the transfer map approach to particle transport, the actual trajectories that the protons follow through the field region do not appear explicitly; in applying pre-computed maps, charged particles are transported from an initial location to a final location in one step by applying the transfer maps to the initial phase space coordinates.

Although the COSY map method provides a fast and accurate method for transporting charged particles in magnetic fields, the transfer map method has several limitations. First, map methods can only be used in void regions. In addition, the Taylor expansions used in applying the maps have a finite volume of convergence in phase space. The convergence volume has a very complicated shape in five dimensions (x, y, dx, dy, p), requiring that the shape of the phase-space volume and the order of the Taylor series needed in order to get a given accuracy in final particle position is not easily predicted in practice and can be checked only by particle tracking. For example, a map to fifth order in energy deviation might be applied with good accuracy to particles with energies within 10% of the reference energy, but not to those with 50% deviation.

Input cards:

COSYP describe the COSY map parameters

Form: COSYP PREFIX AXSH AXSV EMAP₁, EMAP₂, ... EMAP_n

PREFIX	= prefix of the COSY map files
AXSH	= horizontal axis orientation 1 = x-axis, 2 = y-axis, 3 = z-axis
AXSV	= vertical axis orientation 1 = x-axis, 2 = y-axis, 3 = z-axis
EMAP _i	= operating beam energy of the <i>i</i> th map assigned.

Defaults:

AXSH = 1
AXSV = 2

EMAP = energy of the COSY maps

Use: Use with COSY maps

This card specifies the parameters for the COSY maps. The $EMAP_i$ parameter allows the COSY maps to be used for a beam energy that is different than the energy used to create the maps.

COSY assign COSY maps to individual cells.

Form: COSY $M_1, M_2, \dots M_l$

M_i = COSY map number for cell i

Default: No map is assigned to the cell

Use: Use with COSY maps

Assigns COSY map numbers to individual cells

This is a cell parameter card that can also be placed on the cell card.

Example:

```
cosyp 57 2 1 23070 11r
cosy 3j 1 j 2 j 3 j 4 10j 5 j 5 j 6 j 6
```

In this example, the COSY map files are prefixed with 57. The horizontal axis is the y axis, and the vertical axis is the x axis. The operating energy for all twelve maps assigned is 23070 MeV. Field maps are assigned to twelve cells. Table 1 lists the map assignments.

Table 1. COSY Map Assignments

Map Number	COSY Map File Name	Cell Numbers
1	571	4
2	572	6
3	573	8
4	574	10
5	575	21 and 23
6	576	25 and 27

The COSY map files 571, 572, 573, 574, 575, and 576 must be in the working directory.

Particle Ray Tracing

To overcome the limitations of transfer maps, MCNP6 has also implemented direct magnetic field tracking utilizing numerical integration methods. These routines were adopted from the MARS high-energy particle transport code.⁴ Tracking in a void and material is performed by a higher-order numerical integration algorithm, with a maximum step size controlled by the user. Within a step, the trajectory is approximated by a segment of the helical trajectory corresponding to a constant field equal to the field at the midpoint of the step, i.e., the field variation within the step is neglected. A solution of a 3-dimensional equation of trajectory in such a field provides the new direction cosines and new particle coordinates at the end of the step. With appropriate parameters, this algorithm provides extremely high accuracy of tracking.

For quadrupole fields, MCNP includes a model to include the effect of the magnet fringe fields. This can be approximated by applying hard-edge kicks to the particle as it enters and leaves the magnetic field cell. An option for edge kicks has been implemented for the quadrupole magnetic field model. For a particle traveling along the z-axis, the following equations describe the position and momentum jumps applied to a particle as it enters the upstream fringe field of a quadrupole.⁵

$$\delta x = \frac{Gp}{q} \left[\frac{x^3}{12} + \frac{xy^2}{4} \right] \quad (1)$$

$$\delta t_x = \frac{Gp}{q} \left[\frac{xy}{2} t_y - \frac{x^2 + y^2}{4} t_x \right] \quad (2)$$

$$\delta y = -\frac{Gp}{q} \left[\frac{y^3}{12} + \frac{x^2 y}{4} \right] \quad (3)$$

$$\delta t_y = -\frac{Gp}{q} \left[\frac{xy}{2} t_x - \frac{x^2 + y^2}{4} t_y \right]. \quad (4)$$

In these equations, t_x and t_y are the direction cosines of the momentum vector. The quantity G is the quadrupole gradient (in T/m) and p/q is the particle rigidity (in T-m). In order to conserve energy, t_z is also recalculated using the formula

$$t_z = \sqrt{1 - t_x^2 - t_y^2}. \quad (5)$$

For particles passing through the downstream fringe field of a quadrupole, the equations are the same, except that Gp/q is replaced everywhere by $-Gp/q$.

Input card:

The magnetic field tracking option is implemented through the use of a new input data card, BFLD.

BFLDn Magnetic field definition card

Form: BFLD*n* type keyword = value

n = magnetic field number
 type = CONST (dipole field),
 QUAD (quadrupole field), or
 QUADFF (quadrupole field with fringe field edge kicks)

Keywords:

FIELD: magnetic field strength (Tesla) (for CONST field), or
 magnetic field gradient (Tesla/cm) for QUAD and QUADFF fields
 VEC: direction of the magnetic field (CONST), or
 the plane that corresponds to the x-axis of a focusing quadrupole
 MXDEFLEC: maximum deflection angle per step size (mrad)
 MAXSTEP: maximum step size (cm)

These keywords only apply to quadrupole fields:

AXS: the direction cosines of the quadrupole beam axis (does not need to be
 normalized)
 FFEDGES: list of surfaces to which fringe field edge kicks are to be applied. (QUADFF
 only)
 REFPNT: a point anywhere on the quadrupole beam axis

Defaults:

VEC = 1 0 0 (along the x axis)
 MXDEFLEC = 10
 MAXSTEP = 100
 AXS = 0 0 1 (along the z axis)
 REFPNT = 0 0 0

BFLCL assign magnetic fields to the cells

Form: BFLCL M_1, M_2, \dots, M_i

M_i = magnetic field number for cell *i*

Defaults:

$M_i = 0$

Example 1.

```
bfld1 const field .03 vec 0 1 0
bflcl 2j 1
```

A constant magnetic field of strength 0.03 Tesla is applied to cell 3. The field is in the positive y

direction.

Example 2.

```
bfld2 quadff field 0.195 ffedges = 31 2i 34
bflcl 31j 2 0 2
```

A quadrupole magnet field of gradient 0.195 T/m is assigned to cells 32 and 34. Fringe-field edge kicks are applied to surfaces 31, 32, 33, and 34.

Example 3.

```
bfld3 quad field 0.116
vec 0.5 0.5 0.707
axs 0.85 -0.14 -0.5
refpnt 40 30 100
mxdeflc 10 maxstep= 1
bflcl 101j 3 0 3 7j 3 0 3
```

A quadrupole magnetic field of gradient 0.116 T/m is assigned to cells 102, 104, 112, and 114. The axis of the quadrupole is along the vector 0.85 -0.14 -0.5, and the x axis (focusing plane) is along the vector 0.5 0.5 0.707. The maximum step size is 1 cm, and the maximum angular deflection is 10 mrad.

¹ Jeffrey S. Bull, *et al.*, "Magnetic field tracking with MCNP5", LA-UR-04-2125.

² Jeffrey A. Favorite, Kenneth I. Adams, and John D. Zumbro, "Tracking Charged Particles Through Magnetic Fields Using MCNP and MCNPX," LA-UR-99-2809.

³ M. Berz, K. Makino, COSY INFINITY Version 8.1 - user's guide and reference manual, Tech. Rep. MSUHEP-20704, Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, see also <http://cosy.pa.msu.edu> (2002).

⁴ Mokhov, N.V. and Krivosheev, O.E. *MARS code status*. Conference Proceedings -- International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Lisbon, October 2000. (Berlin: Springer-Verlag) (2001) ISBN 3 540 417958; Mokhov, N.V. *Status of MARS code*, Fermilab-Conf-03/053, Fermi National Accelerator Laboratory (2003). (<http://www-ap.fnal.gov/MARS>)

⁵ E. Forest. *Lie algebraic methods for charged particle beams and light optics*. Unpublished Ph.D. Thesis, University of Maryland. (1984).