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MARYLIE 3.0 - A PROGRAM FOR NONLINEAR ANALYSIS OF ACCELERATOR AND BEAMLINE LATTICES*

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Introduction

MARYLIE 3.0 is a Fortran-language beam transport and tracking code developed at the University of Maryland. It employs algorithms based on a Lie algebraic formalism for charged particle trajectory calculations[1], and is designed to compute transfer maps for and trace rays through single or multiple beam-line elements. This is done without the use of numerical integration or traditional matrix methods; all nonlinearities (including chromatic effects) through third (octupole) order are included. Thus MARYLIE 3.0 includes effects one order higher than those usually handled by existing matrix-based programs. In addition MARYLIE is exactly symplectic (canonical) through all orders.

The Lie algebraic treatment of higher order multipoles is under study. MARYLIE 4.0, a MARYLIE version that includes decapole effects, is currently being tested. All versions of MARYLIE have provisions for user written subroutines that permit the treatment of any multipole element by the usual approximations or numerical integration.

Program Organization

MARYLIE is structured to facilitate the input and analysis of both small and very large lattices. It is controlled by a master input file organized into seven components. These components and their purposes are summarized below:

Component	Purpose
#comments	Allows user to write comments about lattice under study, calculations to be performed, etc.
#beam	Specifies magnetic rigidity and relativistic β and γ factors of the beam. Also specifies the scale length to be used.
#menu	Contains a list of user specified beamline elements and commands.
#lines	Contains a list of user speicified names for collections of elements and/or commands drawn from the menu.
#lumps	Contains a user specified list of collections of items from the menu and/or lines that are to be combined together to form individual transfer maps.
#loops	Contains user specified list of collections of elements, lines, and lumps to be used for extensive tracking calculations.
#lattice	Specifies a lattice or beamline, and the actual operations and calculations to be performed.

Experience has shown that the above organization is both flexible and efficient. For example, even lattices as large as those for the proposed Superconducting Super Collider can be completely specified in relatively few lines.

Elements Treated

As indicated above, the #menu component of the master MARYLIE input file contains a list of user specified beamline elements and commands. Each element or command is given a user specified name, and is identified by a type code mnemonic. The beamline elements and their type code mnemonics, as currently available in MARYLIE 3.0, are listed below:

Type Code	Element
drft	Drift Space
	Dipole Bend Magnets
nbnd	a) Normal entry bending magnet, with or without fringe fields.
pbnd	b) Parallel faced bending magnet, with fringe fields and equal entry and exit angles.
gbnd	c) General bending magnet.
prot	d) Used for leading and trailing pole face rotations.
gbdy	e) Used for the body of a general bending magnet.
frng	f) Used for hard-edge dipole fringe fields.
cfbd	g) Combined function bend.
quad	Magnetic Quadrupole, with or without hard-edge fringe fields
sext	Magnetic Sextupole
octm	Magnetic Octupole
octe	Electric Octupole
bnch	Short RF Buncher
arot	Axial Rotation
phad	Rotation in phase space corresponding to a specified set of phase advances
thnℓ	Thin lens approximation to low order multipoles

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Type Code	Element
usr1	User Specified Subroutine
usr2	" " "
usr3	" " "

Commands

The #menu component of the master input file may also contain commands. These commands can be used to manipulate and analyze maps, and perform various ray trace and tracking operations. Commands are also given user specified names, and are also identified by type code mnemonics. The commands and their type code mnemonics, as currently available in MARY 3.0, are listed below:

Type Code	Command
rt	Perform a ray trace.
sqr	Square the existing transfer map.
chro	Compute chromaticities, tunes, and eta functions.
tmi	Input matrix elements and polynomial coefficients for a map from an external file.
tmo	Output matrix elements and polynomial coefficients for a map to an external file.
pmif	Print the contents of master input file.
circ	Set parameters and circulate around a loop.
norm	Compute the normal form for a transfer map.
pnrm	Raise normal form to a power.
end	Halt execution.
ptm	Print transfer map.
iden	Replace existing transfer map by the identity map.
jmap	Replace existing transfer map by J.
inv	Replace existing transfer map by its inverse.
tran	Replace existing transfer map by its "transpose".
revf	Replace existing transfer map by reverse factorized form.
strp	Strip off specified portions of existing transfer map.
symp	Symplectify matrix for a transfer map.

Program Performance

MARYLIE may be used for particle tracking around or through a lattice and for analysis of linear and nonlinear lattice properties. When used for tracking, it is both versatile and extremely fast. Tracking can be performed element to element, lump to lump, or any mixture of the two. The speed for element to element tracking is equivalent to that of any other existing tracking code. When collections of elements can be lumped together to form single transfer maps, tracking speeds can be orders of magnitude faster. For example, experience has indicated that proposed Superconducting Super Collider (SSC) lattices can be treated to high accuracy by using 18 lumps. When so treated, MARYLIE 3.0 can track an SSC lattice for 50,000 turns of full 6-dimensional phase-space motion (including synchrotron oscillations) using less than 6 minutes of CRAY X-MP computer time.

MARYLIE 3.0 also has extremely powerful analytic tools. They include the calculation of first and second order chromaticities, first, second and third order dispersion, the dependence of tune on betatron amplitude, nonlinear lattice functions, nonlinear phase-space distortion, and resonant and nonresonant transfer map normal forms.[2] Indeed, because MARYLIE can be used to give an explicit representation for the linear and nonlinear properties of a one-turn transfer map, it is hoped that this information can be used eventually to predict the dynamic aperture of a ring without the need for long-term tracking.

Simple Nonlinear Example

As an example of the ability of MARYLIE to describe nonlinear behavior, consider the problem of analyzing the performance of a somewhat whimsical imaging system. The system is required to provide unit magnification when acting on rays of 20 TeV protons, and is made with SSC-like magnets. It consists of four quadrupole doublets, and various drifts.

The master MARYLIE input file for this problem is listed below:

```
#comments
    This is a study of a simple imaging system.
#beam
    1.d0   scale length
    6.67d+04  9.99d-01  2.13d+04  brho,beta,gamma
#menu
    dℓ        drft
      100.
    ds        drft
      5.
    qf1       quad
      10.        192.642380   1.   1.
    qf2       quad
      10.        192.642395   1.   1.
    qd1       quad
      10.       -192.642380   1.   1.
    qd2       quad
      10.       -192.642395   1.   1.
    stop      end
    rays      rt
      5  1  1  0
    double    sqr
#lines
    image
      dℓ  qf1  ds  qd2  2*dℓ  qf2  ds  qd1  dℓ  double
#lattice
    image
    rays
    stop
```

The reader will observe the #menu component with its user specified names and type code mnemonics. The numbers listed under the drifts refer to their lengths in meters. The first two numbers listed under the quads refer to their lengths and strengths (in Tesla/meter) respectively. The remaining two 1's indicate the presence of leading and trailing hard-edge fringe fields. The numbers under the ray trace command specify details about the type of ray trace to be performed.

The composition of the optical system is described under #lines. The system has been given the name image, and consists of two identical halves. These two halves are concatenated using the sqr command (user specified name double). The #lumps and #loops features are not used.

Finally, the contents of #lattice causes MARYLIE to compute the transfer map for the system, and trace rays. The initial conditions for the rays are taken from an external file, and the results of each ray trace are written into a second external file.

How well does this magnetic optical system work? Figure 1 shows the image formed when a large number of rays are traced from an object composed of the word MARYLIE (written in two lines). The reader familiar with the subject of image formation will recognize the presence of two major aberrations. First, there is distortion. It accounts for the deformation of the letters M and Y in MARYLIE. Second, there are aberrations that depend on ray direction. They account for the blur in the image. Detailed analysis shows that the total effect is caused mainly by the interplay of third-order distortion, astigmatism, curvature of field, and their higher order consequences due to symplectification.

If desired, MARYLIE can provide quantitative information as to the amount of each aberration present, and identify its source. This can be done simply by using the ptm command to print the transfer map, and then examining the nonlinear content of the transfer map. By doing this, it can be shown that most of the aberrations come from the quadrupole fringe fields. Indeed, figure 2 shows the image produced when the effect of the quadrupole fringe fields is neglected. Now there are no apparent aberrations.

Discussion

The above example gives a brief indication of the ability of MARYLIE to handle nonlinear effects in a simple single-pass system. The same power for nonlinear analysis can also be applied to complicated problems involving large lattices and large numbers of turns. Exactly what can and should be done with these new found abilities is an exciting and very promising area for extensive further research.

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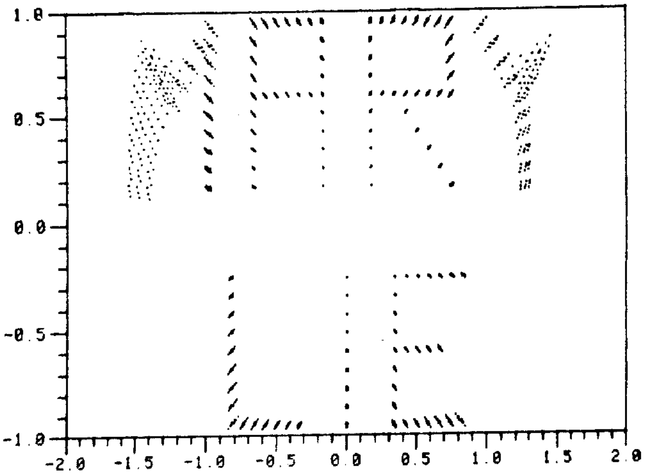

Figure 1. Image of the word MARYLIE produced by simple imaging system including effect of hard-edge quadrupole fringe fields.

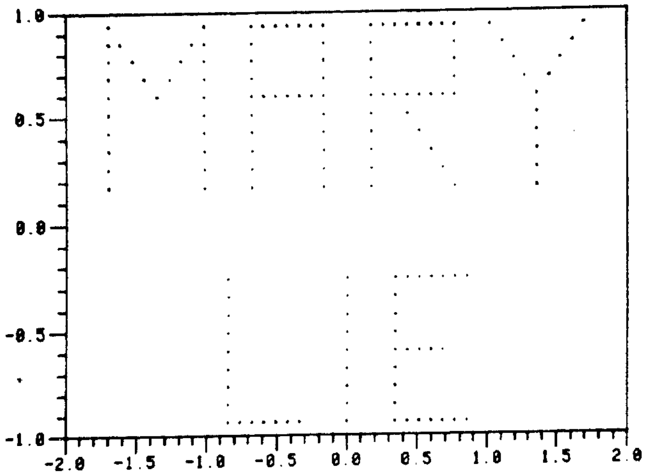

Figure 2. Image of the word MARYLIE produced when effect of quadrupole fringe fields is neglected.