EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TRAJECTORY TRACKING

A number of particles with given initial conditions can be tracked element-by-element throughout a beam-line or a ring, searching for unwanted behavior or particle loss. The particles can be tracked either for a single passage or for many turns.

While MAD-X is keeping most of functionality of its predecessor MAD-8, the trajectory tracking in MADX is essentially modified comparing to MAD-8 [1]. The reason is that in MAD8 the thick lens tracking is inherently not symplectic, which implies that the phase space volume is not preserved during the tracking, i.e. contrary to the real particle the tracked particle amplitude is either growing or decreasing.

The non-symplectic tracking as in MAD8 has been completely excluded from MAD-X by taking out the thick lens part from the tracking modules. Instead of it, two modules realizing a simplectic tracking are implemented into MAD-X.

The first part of this design decision is a thin lens TRACK module which tracks symplecticly through drifts and kicks and by replacing the end effects by their symplectic part in form of an additional kick on either end of the element. This method demands a preliminary conversion of a sequence with thick elements into one composed entirely of thin elements (see the MAKETHIN command). The details of their usage are given in chapter "Trajectory Tracking" for the thin-lens track module.

The second part of this design decision is to produce a thick lens PTC-TRACK module based on PTC [2] that allows a symplectic treatment of all accelerator elements giving the user full control over the precision (number of steps and integration type) and exactness (full or extended Hamiltonian) of the results.

PTC-TRACK module has similar main functionalities as TRACK module (e.g., plotting tracking data). The short user guide for PTC-TRACK module is given below. This module is available in MADX starting from the version 3.0.

TRAJECTORY TRACKING WITH THICK-LENS PTC-TRACK MODULE

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The thick-lens PTC-TRACK module is a kind of an interface to the PTC by E.Forest. The commands accepted by PTC-TRACK are described below, while optional arguments are denoted by square brackets ([ ]) and default values are given in curly braces ({}).

Before starting to track, the working beam line must be selected by means of a USE command. To initialize PTC and define the integration method, corresponding subroutines from "madx_ptc_module.f90" are called with help of the following commands :

PTC_CREATE_UNIVERSE;
PTC_CREATE_LAYOUT, MODEL=integer, METHOD=integer, NST=integer, [EXACT,] OFFSET_DELTAP=double;

The first command "PTC_CREATE_UNIVERSE" is needed to set-up PTC.

The second command "PTC_CREATE_LAYOUT" creates PTC layout and fills it with current MAD-X sequence. The options are explained in the table

Option	Description	Values
MODEL=integer	Type of element	1 (default) => Drift-Kick-Drift; 2 => Matrix-Kick-Matrix; 3 => Delta-Matrix-Kick-Matrix (SixTrack Model);
METHOD=integer	Integration method	2 (default), 4 or 6
NST=integer	Number of integration steps	1(default), 2, 3, ….
EXACT	Treatment of Hamiltonian	IF absent (default), THEN an approximate Hamiltonian; IF exist, THEN an exact Hamiltonian
OFFSET_DELTAP= double	The relative momentum deviation of the reference particle in the 6D case	general for all modules (?????), while default = 0.

Before the PTC_TRACK command, a series of initial trajectory coordinates has to be given by means of a START command (as many commands as trajectories). The coordinates can be either canonical coordinates:

START, X=double, PX=double, Y=double, PY=double, T=double, PT=double;

or action-angle coordinates:

START, FX=double, PHIX=double, FY=double, PHIY=double, FT=double, PHIT=double;

For latter case, the normalised amplitudes are expressed in number of r.m.s. beam size FX, FY, FT (the actions being computed with the emittances in the BEAM command) in each mode plane. The phases are PHIX, PHIY and PHIT expressed in radians. In the uncoupled case, we have in the plane mode labeled by *z*:

$$z = F_z\sqrt{E_z}\cos(\phi_z),\; p_z = F_z\sqrt{E_z}\sin(\phi_z),$$

where E_z is the r.m.s. emittance in the plane $\{z,p_z\}$. The action-angle coordinates are effective, if the normal form analysis is done (the option CLOSED_ORBIT is on). If both the canonical and the action-angle coordinates are given in the START command, they are summed after conversion the action-angle coordinates to the canonical.
If the option CLOSED_ORBIT in PTC_TRACK command is specified (see below), all coordinates are specified with respect to the actual closed orbit (possibly off-momentum, with magnet errors) and NOT with respect to the reference orbit. If the option CLOSED_ORBIT in PTC_TRACK command is absent, then coordinates are specified with respect to the reference orbit.

The track table can be generated at observation points. The first observation is reserved for beginning of the beam-line. Additional observation points can be defined by the statements PTC_OBSERVE (as many commands as additional observation points). It is recommended to use labels of markers in order to avoid usage observations at the ends of thick elements. The syntax is

PTC_OBSERVE, PLACE=label;

The data at the observation points are output either during the element-by-element tracking (ELEMENT_BY_ELEMENT is on) as it is done by earlier MAD versions, or after completing the multi-turn tracking using transfer maps calculated by PTC, if CLOSED_ORBIT is on, RADIATION is off, ELEMENT_BY_ELEMENT is off.

Trajectory tracking is initiated by the PTC_TRACK command. From this command to the corresponding PTC_TRACK_END command MAD-X accepts the tracking statements. Syntax of the PTC_TRACK:

PTC_TRACK, DELTAP=double {0.D0}, ICASE=integer {4}, [CLOSED_ORBIT,] [ELEMENT_BY_ELEMENT,] [RADIATION,] [RADIATION_MODEL1,] [RADIATION_ENERGY_LOSS,] [RADIATION_QUAD,] [BEAM_ENVELOPE,] [SPACE_CHARGE,] [DUMP,] [MAXAPER=array (1:6) {0.1, 0.01, 0.1, 0.01, 1.0, 0.1},] [NORM_NO=integer, {1}] [NORM_OUT,] [ONETABLE,] [FILE=string {track},] [EXTENSION=string {none},] TURNS=integer {1}, FFILE=integer {1}

DELTAP is the relative momentum deviation for off-momentum particles (5D case). It is switched off, if the option CLOSED_ORBIT is off.

ICASE is the user-defined dimensionality of the phase-space (4, 5 or 6). It is internally corrected by the code from 4 to 5, if DELTAP is nonzero.

CLOSED_ORBIT switches on the closed orbit calculation, which must be applied to the closed rings. This option also switches ON the normal form analysis, otherwise it is not performed. If CLOSED_ORBIT is off, the sequence is treated as transfer line.

ELEMENT_BY_ELEMENT defines a way of the particle tracking with PTC. The tracking can be done element-by-element using the option ELEMENT_BY_ELEMENT, or over the whole turn (the option ELEMENT_BY_ELEMENT is off, which is default one). Tracking is done in parallel, i.e. the coordinates of all particles are transformed at each beam element (ELEMENT_BY_ELEMENT is on) or after every turn (ELEMENT_BY_ELEMENT is off) as it is reached.

RADIATION is used to introduce synchrotron radiation calculated by an internal procedure of PTC. It switches off another radiation model (RADIATION_MODEL1 is off).

RADIATION_MODEL1 introduces the radiation according to the method presented in the Roy's paper [3] and programmed as additional FORTRAN module by F. Zimmermann. The model simulates a quantum excitation via random number generator and tables for photon emission. It can be used only with the element-by-element tracking (option ELEMENT_BY_ELEMENT=ON). It is not valid, if another radiation model is used, e.g., if RADIATION is on.

RADIATION_ENERGY_LOSS adds the energy loss for RADIATION_MODEL1. It requires the option RADIATION_MODEL1 is ON, otherwise becomes OFF.

RADIATION_QUAD adds the radiation in quadrupoles. It supplements either PTC radiation (RADIATION is on), or the RADIATION_MODEL1.

BEAM_ENVELOPE switches on calculations of the beam envelope with PTC. It requires the options RADIATION and ICASE=6, otherwise it becomes OFF.

SPACE_CHARGE switches on the simulations of the space charge forces between particles. It requires the element-by-element tracking (the option ELEMENT_BY_ELEMENT is on), otherwise becomes OFF. This option is under construction and is reserved for future use.

DUMP writes particle coordinates arranged as tables into the formatted text files. If the option omitted, then the files are not generated.

MAXAPER specifies upper limits for the particle coordinates. The particle is lost if its trajectory is outside these boundaries. Note, that the thin-lens TRACK module has a special option APERTURE, which switches on the check for the particle losses. The thick-lens PTC_TRACK module has no such special option, since it utilizes PTC tracking procedures, which always checks the particles losses whenever the particles are tracked.

The following two parameters NORM_NO and NORM_OUT are used to support the normal form calculations, which are performed, if the option CLOSED_ORBIT is on:

NORM_NO defines the order of the normal forms, NORM_NO=1 defines linear normal forms, which have been used in previous versions of MAD.

NORM_OUT defines the type of coordinates in output tables: action-angle (NORM_OUT is on) or canonical (NORM_OUT is off).

ONETABLE writes all particle coordinates in a single file, otherwise particle coordinates are written in one file per particle. The output files are named automatically. The name given by the user is followed by .obsnnnn(observation point), followed by .pnnnn(particle number).

FILE is the name for the track table. The default name is TRACK.

EXTENSION is the extension of filename for the track table, e.g., txt, doc etc.

TURNS defines the number of turns (integer) to be tracked (default: 1).

FFILE defines the periodicity for printing coordinates in the output tables, i.e., the output occurs after every FFILE turns.

PTC_TRACK_END is to terminate the command lines related to the PTC_TRACK module.

PTC_END is the PTC end command, which releases all memory back to the MAD-X world proper;

The following table facilitates the choice of the correct options for number of tasks.

Options	1	2	3	4		5	6	7	8	9	9	10
CLOSED_ORBIT	-	-	+	+		+						
ELEMENT_BY_ELEMENT	-	+	-	+	-	-						
RADIATION	-	-	-	-		+						
RADIATION_MODEL1	-	-	-	-		-						
RADIATION_ENERGY_LOSS	-	-	-	-		-						
RADIATION_QUAD	-	-	-	-		+/-						
BEAM_ENVELOPE	-	-	-	-		-						
SPACE_CHARGE	-	-	-	-		-						
START, X, PX, …	+	+	+	+		+						
START, FX, PHIX, …	-	-	+	+		+?						
NORM_NO	-	-	>1	>1		>1						
NORM_OUT	-	-	+	+		+						
PTC_OBSERVE	-	+	+	+		-						

The typical tasks are the following:

1) The tracking in a beam-line where every turn means a period. Input and output particle coordinates are canonical ones.

2) The same as "1)" with element-by-element tracking and an output at observation points located after any element.

3) Tracking in a closed ring. The closed orbit is founded and the normal forms are calculated. Both the canonical and action-angle input/output coordinates are possible. Output can be done at observation points using PTC maps.

4) The same as 3) with element-by-element tracking and output at observation points located after any element.

5) …………………………..

6) ………………………….

The rest of possible tasks including other options are under tests. The users are welcome to submit their tasks for realizations in future releases of MAD-X. The detailed explanation of trajectory tracking with thick lens PTC-TRACK module will be described in [4].

Plotting is not possible inside MADX presently. It can be done externally by using the files created by PTC_TRACK. For some special cases as in examples for PTC-TRACK, one can use WRITE and PLOT commands to produce phase-spaces at beginning of the ring.

References

1. F. Schmidt (MAD-X custodian), "MAD-X PTC Integration", the paper presented at the 2005 PAC Conference in Knoxville, USA, http://cern.ch/Frank.Schmidt/report/MPPE012.pdf
2. E. Forest, F. Schmidt and E. McIntosh, "Introduction to the Polymorphic Tracking Code", KEK report 2002-3, July 2002.
3. G.J. Roy, "A new method for the simulation of synchrotron radiation in particle tracking codes", Nuclear Instruments & Methods in Phys. Res., Vol. A298, 1990, pp. 128-133
4. V. Kapin and F. Schmidt, "PTC-TRACK module for MAD-X code", to be published as CERN internal note by the end of 2005.