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# ADVANCES IN MAD-X USING PTC

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**Abstract**

For the last few years the MAD-X program makes use of the Polymorphic Tracking Code (PTC) to perform calculations related to beamdynamics in the nonlinear regime. An important new feature is the extension of the matching module to allow fitting of non-linear parameters to any order. Moreover, calculations can now be performed with parameter dependence defined in the MAD-X input. In addition, the user can access the PTC routines for the placement of a magnet with arbitrary position and orientation. This facilitates the design of non-standard lattices, in particular since a 3D visualization of a lattice is now available. For the LHC studies during commissioning it is of special interest that one has access to within the thick PTC elements which allows e.g. to find PTC Twiss parameters at any point in the ring.

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# Advances in MAD-X using PTC

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For the last few years the MAD-X program makes use of the Polymorphic Tracking Code (PTC) to perform calculations related to beam dynamics in the nonlinear regime. An important new feature is the extension of the matching module to allow fitting of non-linear parameters to any order. Moreover, calculations can now be performed with parameter dependence defined in the MAD-X input. In addition, the user can access the PTC routines for the placement of a magnet with arbitrary position and orientation. This facilitates the design of non-standard lattices, in particular since a 3D visualization of a lattice is now available.

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## INTRODUCTION

A couple of years ago at CERN the decision was taken to replace the well debugged MAD8 code by MAD-X [1], in view of an easily maintainable code needed for the design and the commissioning of the LHC. Portability, modularity and extensibility have been design goals, in particular to complement MAD-X with the independent PTC code [2]. The MAD-X code is organized by one custodian and several module keepers at CERN and other laboratories (see Table 1). In fact, international collaboration for MAD-X is very welcome. Documentation, examples, source code and executables can be found at the MAD-X web page [3].

Since its introduction MAD-X has been fully employed for all CERN's accelerator and transfer lines (see the CERN CVS accelerator repository *CAMIF* [4]. Various laboratories like Daphne, BNL, GSI and more recently PSI have adopted MAD-X as one of their main accelerator design tool and they have accepted active roles in further developing the code.

## SUPPORT FOR TRANSFER AND ACCELERATING LINES

In the initial implementations of the MAD-XP transfer and accelerating lines were not properly treated. Therefore we have extended the interface between MADX and PTC, updating all the adequate data structures such that they are capable to handle linear layouts with longitudinally varying reference beam energy. We have added a switch that instructs the code to treat a given layout as a ring or a line. The code has been safeguarded against the misuse of the algorithms, e.g. the normal form cannot be performed for a Linac. The appropriate user interface for the Traveling Wave Cavity, the TWCAVITY element, has been added. On request, the settings can be automatically adjusted to the user needs, e.g. the phase of the wave with respect to the reference particle.

| Platform | Responsible |
|---|---|
| LINUX | Frank Schmidt |
| MAC OSX | Helmut Burkhardt |
| Windows | John Jowett |
| **Module** | **Keeper** |
| MAD-X C Core | Hans Grote |
| | Ilya Agapov, Piotr Skowronski |
| APERTURE | Bernard Jeanneret |
| C6T | Frank Schmidt |
| CORORBIT | Werner Herr |
| DYNAP | Frank Zimmermann |
| EMIT | Rogelio Tomas |
| ERROR | Werner Herr |
| FOOT | Frank Schmidt |
| IBS | Frank Zimmermann |
| MAKETHIN | Helmut Burkhardt |
| MATCH | Riccardo de Maria |
| PLOT | Riccardo de Maria |
| PLUG-IN SUPPORT | Piotr Skowronski |
| PTC proper | Etienne Forest KEK |
| PTC_NORMAL | Frank Schmidt |
| PTC_TRACK | Valery Kapin ITEP (RU) |
| PTC_TRACK_LINE | Piotr Skowronski |
| PTC_TWISS | Ilya Agapov |
| SODD | Stefan Sorge GSI |
| SURVEY | Frank Tecker |
| SXF | Nikolay Malitsky BNL |
| THREADER | Thys Risselada |
| TOUSCHEK | Catia Milardi IFNL/LNF |
| | Frank Zimmermann |
| TWISS | Frank Schmidt |
| THINTRACK | Alexander Koschik |

Table 1: Platform Support & Module Keepers.

## MOMENTS OF THE DISTRIBUTION

Knowing the transformation map $\mathcal{M}$ of order N and the initial distribution of particles one is able to compute moments up to order 2N. An arbitrary moment $\langle \mu_{ij} \rangle$ is given by:

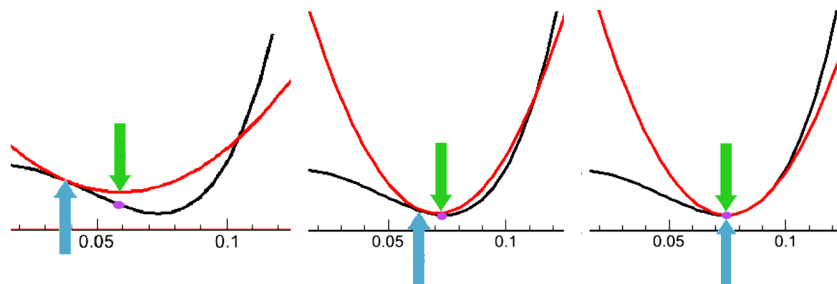$$\langle \mu_{ij} \rangle = \int x^i p_x^j \, \rho(\vec{X}) \, d\vec{X} \qquad (1)$$

Figure 1: Schema of matching employing knobs for a simple example with one variable. Horizontal, vertical axis represent the variable and the penalty function value respectively. The black line represents the penalty function. The red line shows its Taylor approximation. The blue up-pointing arrow indicates the currently guessed value. The green arrow shows the minimum of the approximation and the violet dot the corresponding value of the penalty function. The minimum of approximation becomes the new guess point. The algorithm stops when the two arrows are within the specified tolerance.

for simplicity the derivation is restricted to one dimension, where $\vec{X} = (x, p_x)$ are the phase space coordinates and $\rho$ is the density of the distribution. We substitute $x = \mathcal{M}_x(\vec{X}_{ini})$ and $p_x = \mathcal{M}_{p_x}(\vec{X}_{ini})$, where $\mathcal{M}_x$ and $\mathcal{M}_{p_x}$ are components of the map that expresses $x$ and $p_x$ via the initial vector $\vec{X}_{ini}$, respectively. Due to symplecticity of the map we have: $\rho(\vec{X})\, d\vec{X} = \rho(\vec{X}_{ini})\, d\vec{X}_{ini}$.

$$\langle \mu_{ij} \rangle = \int (\mathcal{M}_x(\vec{X}_{ini}))^i (\mathcal{M}_{p_x}(\vec{X}_{ini}))^j \rho(\vec{X}_{ini})\, d\vec{X}_{ini}$$

(2)

Since $\mathcal{M}_x$ and $\mathcal{M}_{p_x}$ are polynomials the formula above takes the form of the sum of the components having the following form:

$$\mathcal{M}_{xn}^k \mathcal{M}_{p_x m}^l \int x_{ini}^{k'} p_{x\,ini}^{l'} \rho(\vec{X}_{ini})\, d\vec{X}_{ini}$$

(3)

where $\mathcal{M}_{xn}$ and $\mathcal{M}_{p_x m}$ are particular coefficients of the polynomials. Hence, a moment of the distribution depends solely on the map and moments of the initial distribution. The latter can be calculated having the initial shape of the beam.

The user defines moments to be calculated with the help of the PTC_SELECTMOMENTS command. The PTC_MOMENTS command calculates them using the map obtained by the most recent PTC_TWISS invocation. As the consequence, the maximum order is limited by the order requested in PTC_TWISS. The user must provide the initial type of the distribution in each of the planes. Currently the following distribution types are accepted: Gaussian, rectangular and delta-rectangular (i.e flat in one dimension, and delta in the conjugated one, f.g. flat in $p_t$ delta in $t$). In case the user is interested in the calculation of the lower orders, PTC_MOMENTS provides the appropriate parameter.

## KNOBS

PTC allows additional parameters in the calculations which we refer to as knobs. All lattice functions and map coefficients can be represented as functions (Taylor series) of the knobs.

We have developed the PTC_SETKNOB command that defines one or more of the following parameters as a knob: any field component up to order 100, voltage, frequency, phase of a cavity, field strength of a solenoid and Twiss parameters (only uncoupled) at the beginning of a line.

All standard lattice functions as well as map coefficients and other nonlinear parameters selected by the user are available in the form of polynomials.

A knob value is the deviation from the nominal value around which the Taylor series is expanded. The command PTC_SETKNOBVALUE sets a given knob to a certain value. As a consequence, the scalar values of the lattice functions stored in the tables are re-evaluated using the polynomial representation.

## MATCHING OF PARAMETERS TO ARBITRARY ORDER

The matching module of MAD-X has been updated in order to extend its functionality to more sophisticated fitting procedures, some of which are based on PTC calculations [5]. The user can define a macro that is executed at each matching step. It may contain an arbitrary set of MAD-X commands including calls to PTC. Additionally, the matching constraints may refer to an arbitrary cell in a table or a user-defined expression. The two new commands, PTC_SELECT and SELECT_PTC_NORMAL, instruct the PTC_TWISS and PTC_NORMAL procedures, respectively, to store the selected parameters of arbitrary order in the specified tables.

## FAST MATCHING WITH THE HELP OF KNOBS

The high complexity of the calculations performed by PTC is associated with large computational times. It is especially noticeable in the case of the matching procedures, where the calculation must be performed several hundred or even thousands of times. The performance of the procedure is significantly increased if faster derived albeit ap-

proximate results are exploited.

The algorithm that we have developed is illustrated in Fig.1. The variables that the user aims to match are set as knobs. All the lattice functions and other parameters used in the constraints become Taylor series expanded around the first (guessed) starting point. Then the minimum is found on the basis of the Taylor series, which is a very fast procedure. Of course, the search must be limited to some user defined validity range where the approximations are sufficiently accurate. The minimum as found in this procedure becomes the new guessed value, the lattice parameters are updated accordingly and the PTC calculation is repeated. The algorithm stops if both of the following conditions are fulfilled: a) the minimum is found for sufficiently small values of the knobs (Taylor series is exact at the point where it was expanded), b) the value of the penalty function evaluated for these knobs is within the required precision close to the one obtained with Taylor series. Please note, that the second point needs an additional PTC run. More detailed method description of the method together with the manual is available on our web page [3].

## ELEMENT PLACEMENT AT ARBITRARY POSITION AND ORIENTATION

PTC routines can be used that permit to displace elements to arbitrary positions and orientations. This feature facilitates the design of non-standard lattices. The user can define new element position and orientation with respect to: (current position, end face of the previous element, origin of the global coordinate system). If requested, the program adjusts automatically the positions of all elements downstream of the displaced element.

## 3D VISUALIZATION OF LATTICES

The details of the geometry described in PTC can be written to a file using the PTC_PRINTFRAMES command. One of the supported formats is a ROOT macro [6]. When executed with ROOT, a 3D image of the layout is displayed. Root supports intuitive mouse based navigation as well as a keyboard based one. The user can zoom and rotate the image in an arbitrary plane. The hope is that this feature is not just a gimmick but will be used to facilitate lattice design that may require non-trivial geometric transformations. It might even be useful to verify that a particular ring closes as expected.

## PLUG-INS

We have defined a C interface to MAD-XP that opens the possibility for the development of plug-ins that extend the standard functionality of the code. The user may define new commands that are implemented in the specified shared library. On request of such a command the library is dynamically loaded and the specified function is called.

This interface allows for the interaction and data exchange between user defined modules and MAD-XP. The first available plug-in is RPLOT. It is a ROOT [6] based graphical tool that plots the parametric lattice functions. These functions can be depicted: (at a given location as a function of one or two parameters and along the layout). This interface allows to control the knobs and formats of the plots which can be saved in the following formats: Postscript, PDF, JPG, GIF and others.

## CONCLUSIONS

We have described the newest features of MAD-X that take advantage of the PTC capabilities leading to increased functionality in the combined code MAD-XP. The new commands extend the existing MAD language and are easy to use.

Linear machines are now better supported in MAD-XP. Thanks to the implementation of the parametric knobs the user is able to study more effectively properties of a lattice as a function of its parameters. Consequently, the matching module could now be extended to deal with parameters of any order. Moreover, the parametric matching allows for a significantly speed-up of the matching procedure.

The user can now displace the elements to arbitrary positions. New ways to visualize a layout in 3D are also provided. The concept of plug-ins has now been implemented into MAD-X, first of which is RPLOT that uses the ROOT capabilities for plotting the parametric lattice functions.

By interfacing MAD-X with PTC (MAD-XP) we have provided a more complete and user friendly program for particle accelerator design and modeling. Driven by the needs of future machines like CLIC, MAD-XP is constantly improved to tackle ever more complex tasks.

Most relevant is the fact, that those new features are available for the LHC pre-accelerators, transfer lines and the LHC itself. They are already heavily in use.

With these new features and many bug fixes we are at MAD-X version 3.4. For the autumn 2007 we are gearing up for the LHC commissioning version 4.0 once the PTC thin lens lattice is fully implemented and the beam-beam interaction is included.

## REFERENCES

[1] H. Grote and F. Schmidt, 2003 PAC Conference.

[2] E. Forest et al., KEK Report 2002–3.

[3] http://mad.home.cern.ch

[4] CAMIF CVS root at http://isscvs.cern.ch/cgi-bin/cvsweb.cgi/?cvsroot=ccdb.

[5] R. de Maria et al., ICAP'06, Chamonix.

[6] http://root.cern.ch