UPGRADE OF SLICING AND TRACKING IN MAD-X

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Abstract

We describe the extension of the functionality of the slicing module and its applications in MAD-X. The added features allow to select thick or thin slicing for individual quadrupoles or groups of quadrupoles and allow tracking of thick quadrupoles and dipoles in MAD-X. Complex dipole magnets with fringe fields can now automatically be translated to simple bends with extra dipedges.

INTRODUCTION

MAD-X [1] is a program widely used in designing and simulating accelerators. Within MAD-X, the MAKETHIN module provides an automatic translation of the thick lens descriptions of the magnetic lattice, to a symplectic thin lens lattice description, suitable for tracking codes.

In a previous conference contribution, we described the extension of the TEAPOT algorithm [2], which is very effective in positioning quadrupole slices [3].

ENHANCED FUNCTIONALITY

How individual magnets, groups of magnets or element classes will be sliced can be specified using a standard MAD-X select statement of the kind:

```
SELECT, FLAG=makethin, RANGE=range,
   CLASS=class, SLICE=n, THICK=true,
   PATTERN=pattern[,full][,clear];
```

By default, MAKETHIN translates a sequence with thick elements to a sequence consisting only of thin elements, using n slices per element. We have upgraded the selection for MAKETHIN such that slicing can now be turned off by specifying a number of slices below 1 for a given class of selected elements. This is very useful to determine the source of tune changes and β-beating in slicing. As an example

```
SELECT, FLAG=makethin, CLASS=sextupole,
   SLICE=0;
```

will turn off the slicing of all sextupoles, while other magnets will be sliced using the default behaviour.

We also added an extra option ”thick” to the selection for MAKETHIN. By default it is set to false. If set to true, MAKETHIN will produce thick magnet slices. At present, this is only effective for bending and quadrupoles magnets, and ignored otherwise.

THICK QUADRUPOLE SLICING

Figure 1 illustrates thick quadrupole slicing using TEAPOT style [3]. For $n = 0$, the quadruple is not sliced

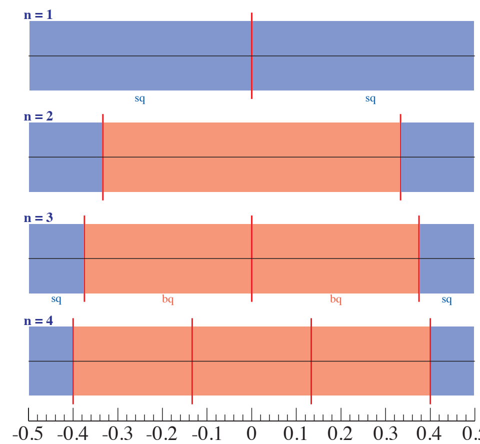

Figure 1: Illustration of thick quadrupole slicing where colours represent the different lengths of the slices.

(1 piece). With $n = 1$, the quadrupoles is cut once in the middle in two pieces of same length tagged sq (blue). For $n = 3$ the magnet is cut three times, resulting in four thick quadrupole pieces of two different lengths tagged sq (blue) and bq (orange) respectively. The optics Twiss parameters are not changed by thick quadrupole slicing. Thick slicing allows to add markers or multipole errors at the transitions.

BENDING MAGNETS

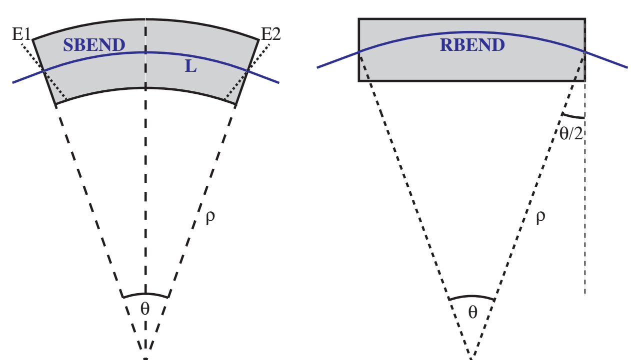

Figure 2: Schematic view of the two basic bending magnet types used in MAD-X. The sector magnet SBEND, and the rectangular magnet RBEND.

MAD-X has two types of bending magnets, the sector magnet SBEND and the rectangular magnet RBEND, which a specific case of SBEND with parallel pole faces (i.e. with $E1 = E2 = \theta/2$), as shown schematically in Fig. 2. For both types, the main parameters are the arc length of the magnet L and the bending angle θ, such that $L = \rho\theta$, where ρ is the radius of curvature. Note that the straight length of the RBEND is shorter than the path length by the factor $\frac{2}{\theta}\sin\frac{\theta}{2}$. This straight length can be optionally specified using the input parameter RBARC=false.

In order to take care of the fringe fields and edges focusing around thick sector bends, we added a new option MAKEDIPEDGE to MAKETHIN. When set to true, this option automatically generates thin DIPEDGE elements around the thick body of the SBEND, which would otherwise be lost in the translation by MAKETHIN. For instance, a thick magnet defined as:

```
mb1: sbend, L:=l, angle:=ang, K1:=k1,
   E1:=e1, E2:=e2, hgap:=gap, fint:=fin;
```

will be translated to

```
mb1.edge_l: dipedge, h:=ang/l, E1:=e1,
    hgap:=gap, fint:=fin;
 ! new dipedge at start
mb1.body: sbend,l:=l, angle:=ang, K1:=k1,
   edge=false;
 ! bend with edge effects removed
mb1.edge_r: dipedge, h:=ang/l, E1:=e2,
    hgap:=gap, fint:=fin;
 ! new dipedge at end
```

The DIPEDGE element has zero length and will directly be copied in slicing by MAKETHIN. After slicing, the thin bend becomes

```
mb1: multipole, lrad:=l, knl:={ang,k1*l};
```

The original length is kept as `lrad` parameter to allow for the calculation of synchrotron radiation effects in thin lattices. MAKETHIN automatically translates the straight RBEND length to the curved length if required (RBEND, RBARC=false).

APPLICATIONS

Figure 3 shows an application of the upgraded functionality for the LHC, illustrating the impact and necessity of the added DIPEDGE elements. In this example, the slicing has been turned off for all magnet types, except for the bending magnets where only one slice (i.e. $n = 1$) has been specified in order to add the DIPEDGE elements and make their effect visible.

Dipole slicing without DIPEDGE elements introduces a β-mismatch on the level of several hundred ppm in the LHC. The horizontal mismatch is reduced by a factor of 20 when DIPEDGE generation is turned on, and becomes negligible in the vertical plane.

As second example, we show the effect of slicing on a smaller circular machine, the low energy ion ring LEIR at CERN [4]. It has a circumference of 78.544 m that includes 4 bending magnets with angle of 90° each, and has tunes of $Q_x = 1.667, Q_y = 2.720$. Figure 4 shows as solid lines the β functions of the original thick LEIR lattice. Without DIPEDGE generation, the MAD-X twiss calculation fails to find a stable solution after MAKETHIN, even

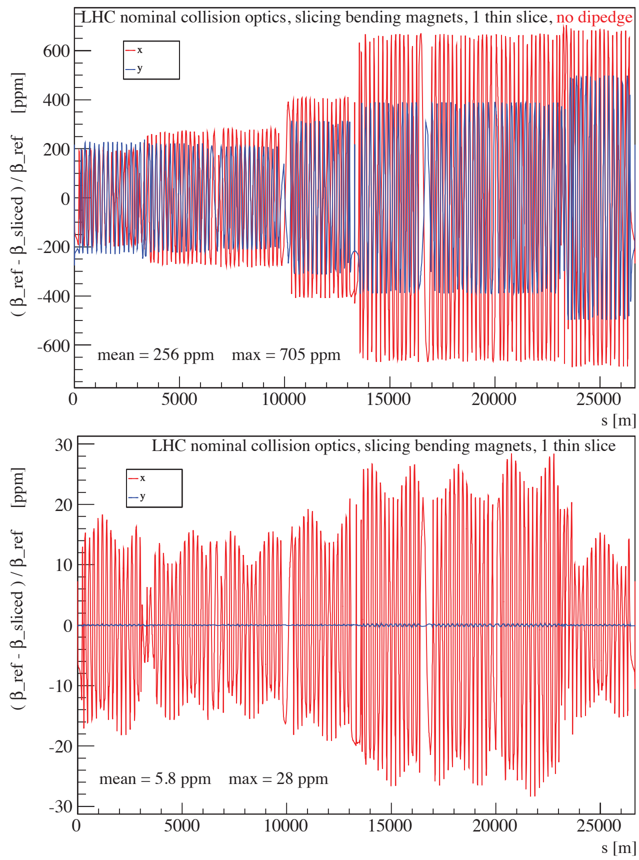

Figure 3: β-mismatch introduced in the LHC (design collision optics V6.503) in slicing only bends, using a single thin slice. Top is without and bottom with dipedge generation.

when many slices are selected. The dashed lines in Fig. 4 show the β-functions obtained using the TWISS module with the initial parameters of the original lattice. One can see that the β-functions become incorrect if the DIPEDGE elements are not included.

The situation is improved when the DIPEDGE generation is turned on. The Twiss module of MAD-X finds correctly a stable solution, already for single thin slice. The β-mismatch is reduced below the 10^{-3} level, with only 4 thin quadrupole slices and 2 thin bend slices, see Fig. 5. Further studies will we performed to verify the effects of the DIPEDGE elements on the dispersion function.

TRACKING THROUGH THICK QUADRUPOLES

MAD-X version previous to 5.02.00 was able to perform particle tracking only through thin elements. Hence a beam line had to be converted into its thin-lens approximation using the MAKETHIN module. The disadvantage of tracking through thin-lenses is that, to achieve sufficient accuracy, it is often necessary to slice an element in many thin lenses to replace just one thick element and to rematch to optical pa-

ISBN 978-3-95450-132-8

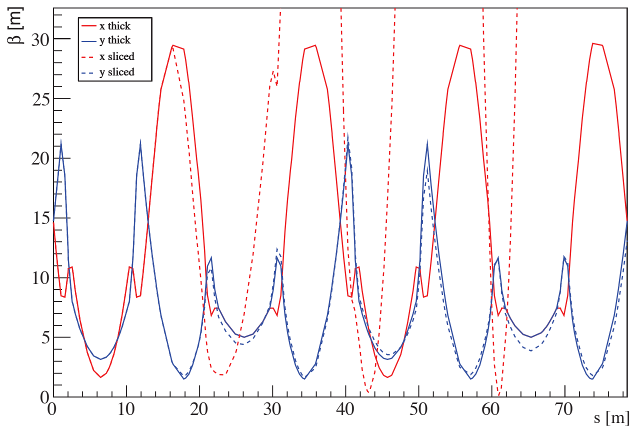

Figure 4: β-functions for LEIR with and without edge field focusing (dipedges turned off).

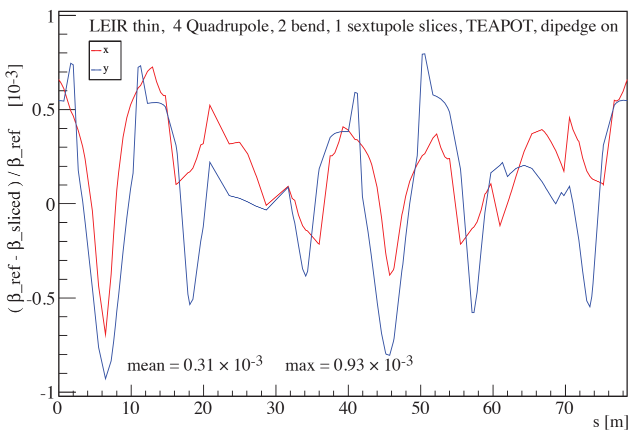

Figure 5: β-mismatch in LEIR with DIPEDGE generation, reduced below 10^{-3} using TEAPOT slicing with 4 thin quadrupole and 2 thin bend slices.

rameters (e.g. the tunes). Starting from version 5.02.00, an option to track quadrupoles as thick lenses has been added to MAD-X. This option can be enabled using the same command SELECT for MAKETHIN as mentioned before. For example, the command:

```
select, flag=makethin, class=quadrupole,
    thick=true;
```

will inform MAKETHIN to treat all quadrupoles in the lattice as thick elements. This option is compatible with the element slicing option, using the thick maps instead of the drifts.

The details of the implementation, including the details of the derivation of the equations of motion from the exact and the expanded Hamiltonian, are presented in [5]. This new code implements full 6D tracking, including second order terms in the longitudinal coordinate, in order to compute the path length difference due to position, angle and momentum offsets at the entrance of the quadrupole.

TRACKING THROUGH THICK BENDING MAGNETS

Similarly to the tracking with thick quadrupoles, the tracking with thick dipoles has been recently implemented in the tracking module of MAD-X and can be enabled through the command:

```
select, flag=makethin, class=dipole,
    thick=true;
```

As for quadrupoles, it will inform MAKETHIN to treat all the dipole magnets of the lattice as thick elements. This option is compatible with the element slicing option, using the thick maps instead of the drifts.

The details of the implementation, including the full derivation of the equations of motion from the exact and from the second-order expanded Hamiltonian, are presented in [6]. This new tracking routine implements only the body of a bending magnet, which will come equipped with the DIPEDGE elememts by the MAKETHIN module, as described in the previous sections. The implementation takes into account the longitudinal coordinate and the path length difference due to the incoming particle position and angle offsets.

SUMMARY, OUTLOOK

We have upgraded the MAKETHIN module and the tracking functionality of MAD-X to handle properly thick dipoles and quadrupoles. Dipole fringe fields can now automatically be taken into account by DIPEDGE generation. We have implemented thick dipole and quadrupole tracking including path length differences to the second order.

ACKNOWLEDGMENT

The authors wish to thank Riccardo De Maria for the useful discussions and inputs, and all members of the MAD-X team for their constant support.

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