

MAD-X FOR FUTURE ACCELERATORS

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Abstract

The feasibility and performance of the future accelerators must, to a large extent, be predicted by simulation codes. This implies that simulation codes need to include effects that previously played a minor role. For example, in large electron machines like the FCC-ee the large energy variation along the ring requires that the magnets strength is adjusted to the beam energy at that location, normally referred to as tapering. In this article, we present new features implemented in the MAD-X code to enable and facilitate simulations of future colliders.

INTRODUCTION

MAD-X was first released in 2002, and has been extensively used to perform beam dynamics studies at CERN and globally since its launch [1]. The original development was focused on the design of the Large Hadron Collider (LHC) optics but has since then been used for several different machines and studies. MAD-X is still currently at the center of many studies of optics, aperture, emittance and tracking. Cppmad, a python interface to MAD-X, has recently grown in popularity [2]. It enables the user to interact with the MAD-X environment in a more pythonic way and to retrieve tables directly into the python environment. MAD-X is also crucial in the creation survey files and for making the input files to SixTrack which is used for long term Dynamic Aperture studies [3]. Finally, it also provides an interface to the powerful Polymorphic Tracking Code (PTC) [4]. This diversity with many modules makes it a powerful tool but it also adds complexity since any change or fix needs to be propagated to the different parts of the code.

In this article, we focus on the recent developments of MAD-X in terms of performance, physics and of the functionalities that make up the MAD-X language. All the new features for each release, *e.g.* the recently implemented RF-focusing, can be found on the website under *Releases* [1].

TRACKING

MAD-X has a tracking module where one or several particles can be tracked. This can be used, for example, to simulate optics measurements. The MAD-X tracking module has historically been used for thin tracking, but thick dipoles, quadrupoles and solenoids are also available. Radiation is also included in the tracking module and the behaviour has been cross-checked against MAD-8 and PLACET [5–8]. In order to speed-up the code to be more usable for large machines, code profiling was performed. It was discovered that a significant amount of time was spent on internally retrieving the variables, and by caching them at the start of the tracking module we were able to speed-up MAD-X significantly. Figure 1

shows a comparison of the number of turns per second before and after this improvement was introduced for a thin lattice of the LHC and FCC-ee. In the case of the FCC-ee, radiation is also included in the tracking. We observe that in both cases the speed is increased by nearly a factor 10. It should however be noted that the relative speed-up will be less significant when many particles are simulated at the same time.

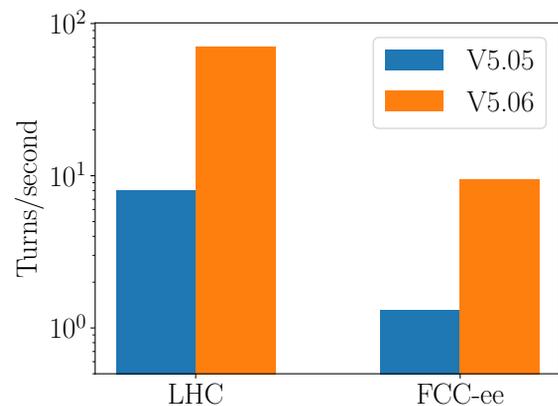


Figure 1: The number of turns per second for a single particle before (V5.05) and after the improvement in retrieving the attributes (V5.06). In the FCC-ee case radiation is enabled.

Particle Distribution

The functionality to create matched particle distributions in MAD-X has been introduced. It provides the possibility to generate either a Uniform or Gaussian distribution. The user can also apply cuts in the number of σ on the distribution. In Fig. 2 an example of a Gaussian distribution cut at 3σ and a hollow uniform distribution is shown. The creation of the distribution is based on the de-normalization matrix, which is calculated from the linear one-turn map in the twiss module. It is therefore possible to create matched distributions also when there is a strong coupling between the planes.

ARBITRARY BEAM SCREENS

There are several pre-defined beam screens in MAD-X *e.g.* a circle or a rectangle. However, in certain machines, such as the Proton Synchrotron (PS) they are unable to fully describe the geometry of the actual beam screen limiting the available aperture. A method to check if particles are inside an arbitrary polygon has therefore been implemented. It is available for both MAD-X and PTC tracking. The method used is referred to as the winding method, which, as the name suggests, checks if the polygon winds around the point [9]. This check is relatively slow, in case there are many sides to the polygon. In order to avoid the full check every time a particle passes through, a pre-check has been implemented.

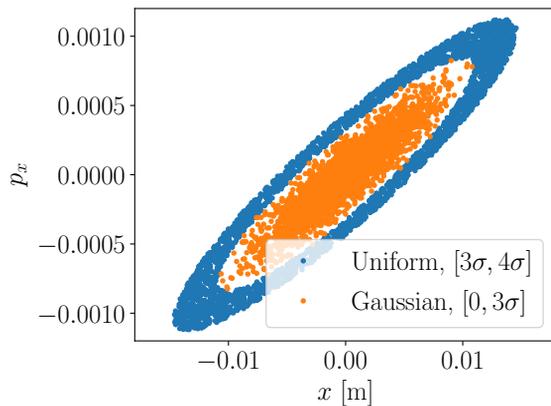


Figure 2: An example of two generated distributions. A Uniform hollow distribution where only particles between 3σ and 4σ are included and a Gaussian distribution where particles above 3σ are removed.

It works by allowing the user to define a simpler aperture based on the pre-defined beam screens as a first check. If the particle is outside this first check, it then verifies if the particle is still inside the arbitrary polygon. In case it is outside both of them, the particle is considered lost. An example of a toy aperture is shown in Fig. 3. The blue dots indicate the lost particles after the aperture restriction and the orange dots represent those that are still in the machine.

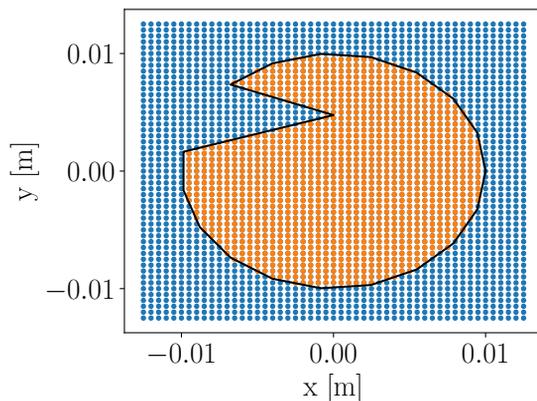


Figure 3: An example of a beam screen implemented as polygon (black line). The blue dots show the particles lost and the orange shows the particle still within the aperture.

The functionality to define an arbitrary geometry with deferred expressions has also been implemented. This, in combination with the UPDATE command in the track module, provides the functionality to change the beam aperture during a tracking simulation. This could be used to simulate *e.g.* the impact of moving a collimator.

MAD-X COMMANDS IMPROVEMENTS

Add to an Expression

One of the strengths with MAD-X code is the possibility to use deferred expression in the definition of a variable, or a

magnet strength. This enables the users to define dependencies between variables and then simply changing the value of one variable, which then causes the dependent variable to be updated. This is an efficient way of creating *e.g.* knobs. In the past, these expressions were static, meaning that it was not possible to append additional dependencies to a variable. This makes it challenging to create additional knobs after the sequence has been defined. A new function in MAD-X solves this and hence enables users to fully exploit the power of the deferred expression in scripts. An example of this new feature is given below:

```
a := b + c;
add2expr, var=a, expr=-d;
show, a;
a := b + c - d;
```

The Move Command

It can be useful to move an element in a sequence in the design phase of an accelerator. It is possible, in MAD-X, to assign an element in a sequence a relative location, *e.g.* `q1,at=2, from=IP1`, in this case 2 meters after IP1. In the past, the use of the move command resulted in a new sequence where all the elements were given as an absolute position from the start of the sequence. This can make later manipulation of the sequence difficult. A method to keep the relative position after a move has therefore been implemented.

Hexadecimal Format

It is possible to save a sequence or assigned magnet errors in MAD-X. The saving is done in ASCII format, which results in small numerical differences when loaded again. Even if these differences are too small to have a real impact of the physics, they can cause confusion and make it harder to debug any potential issues. The possibility to save and load the double precision floating point numbers in a hexadecimal format has therefore been implemented. In this way, it is possible to obtain the exact same representation after a sequence has been saved and then reloaded.

PERMANENT MISALIGNMENT

The elements in a lattice are normally placed on the reference orbit. However, sometimes the elements are misaligned on purpose, *e.g.* a quadrupole might be horizontally misaligned to create a dipole kick through feed-down. The functionality to misalign elements was already available in MAD-X, but the misalignment had to be assigned with a special command and the definition could not be included in the sequence. We have therefore implemented a functionality to be able to define a permanent misalignment to an element in a sequence. An additional survey option has been added, to create a survey table where the permanent misalignments of the elements are included. An example of a system where the elements are misaligned with respect to the reference orbit is the interaction region of the FCC-ee. In this case the solenoids are installed with an angle of 0.015 rad with respect to the reference orbit in the horizontal

plane. The vertical dispersion in a solenoid, followed by an anti-solenoid (opposite direction of the fields) is shown in Fig. 4. The misalignment is also exported to PTC and we see that the two codes agree well with each other for the calculation of the vertical dispersion.

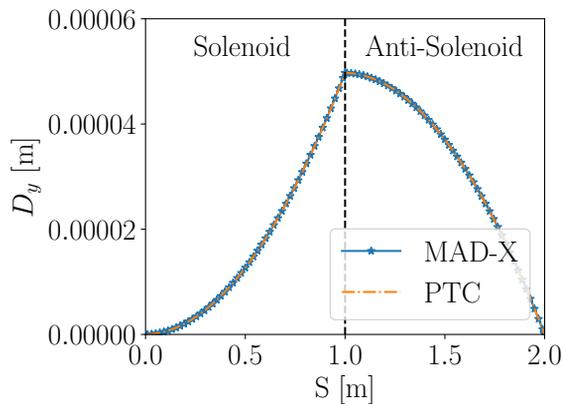


Figure 4: The vertical dispersion for a 1 m solenoid followed by a 1 m solenoid with the opposite strength (anti-solenoid).

TAPERING

The FCC-ee is a lepton machine where the energy variation around the ring will be so significant due to radiation that we need to adjust the strength of the magnets locally to the beam energy. One of the key functionalities needed for this was the separation between the strength of the magnetic field and the change of reference frame from the bending magnets through their angles. This is done by defining an integrated field strength $K0 \cdot L$ different from the angle for the dipole. The separation of strength of the dipole and the bending of the reference frame is also need for other machines such as the proposed Electron-Ion Collider (EIC) [10]. When tapering a lattice the $K0$ is adjusted inside MAD-X based on the average momentum deviation in the bending magnet. This is an iterative process since the optimal phase of the RF system also needs to be found to compensate for the overall radiation. In MAD-X this has been solved by using the general matching command for the phase of the RF-cavities while constantly adjusting the strength of the magnets. The strength of the other magnets are also adjusted to obtain the same focusing and impact on chromaticity as the nominal optics without radiation. The tapered lattice can be saved and the strength derived from the tapering is stored in a parameter with the naming convention *e.g.* $K1 \rightarrow K1_{tap}$. In Fig. 5 the relative deviation of the β -function between the tapered lattice with radiation compared to the nominal lattice without radiation is shown together with the energy deviation in case of radiation. We notice that the relative deviation of the β -function follows well $-p_t$ (in this configuration it is almost identical to the relative momentum deviation). This can be understood from the fact that emittance in the MAD-X formalism never changes and hence the β -functions need to reflect the correct beam size. This means that the saw-

tooth observed in this lattice is in fact the change in beam size due to the adiabatic damping. The results have also been cross-checked with the SAD code [11, 12].

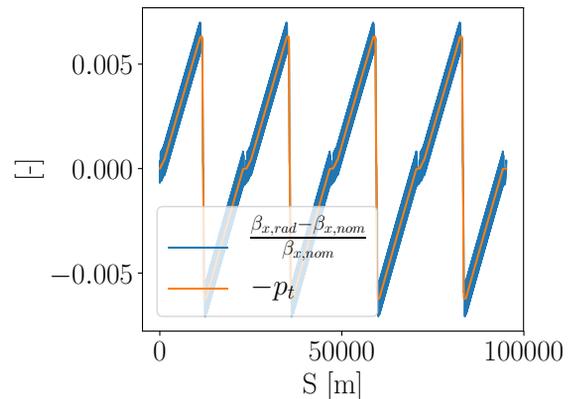


Figure 5: The relative deviation of the β -function between the tapered lattice and nominal for the FCC-ee (182.5 GeV).

CONCLUSION AND OUTLOOK

Despite being almost 20 years old, MAD-X is still a workhorse for optics design and many other beam dynamics simulations [13]. We have in this article shown recent development and improvements to the MAD-X code. One of the crucial improvements is the separation between the strength of a bending magnet and the definition of the curvature of the reference orbit. This change paved the way for simulation of the EIC and creating tapered lattices needed for the FCC-ee. The possibility to place elements away from the reference orbit has also been included through the implementation of the permanent misalignment. These features allow building lattice representations much closer to real layouts.

Additional features that are under investigation, to get even more accurate simulations, are fringe fields for solenoids and quadrupoles and overlapping fields. An accurate description of complicated fringe fields could be explored through the implementation and use of generalized multipoles [14, 15]. Symplectic thin combined function magnet [16] are also planned as future additions.

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