REVIEW OF LHC ONLINE MODEL IMPLEMENTATION AND OF ITS APPLICATIONS

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Abstract

The online model of the LHC aims to provide an accurate description of the machine at any given time. In order to do so it extracts the current optics in the machine along with other crucial parameters. It also provides the functionality to match the measured orbit using virtual correctors and the measured beta functions using virtual quadrupoles. In this way an accurate effective model can be created. In order to facilitate the use of the online model a graphical user interface has been developed. In this article we describe the design of the online model and its application in different studies. We give examples of how it has been used to predict the influence of changes before they were applied to the machine.

INTRODUCTION

The modelling plays a fundamental role in the design and operation of modern accelerators. The model is created from the design and measurements of the magnets and the layout of the accelerator. The online model of the LHC aims to create an effective accurate model, which can be used to simulate new settings and effects. The model can also be used for more precise and more realistic simulations compared to the nominal model. It also provides more accurate inputs for model-based measurements and corrections.

The modelling of the optics is done in MAD-X [1]. In order to obtain the additional input a tool has been created to extract parameters that are of interest for the online model. The implementation is done in such a way that it gives the user the possibility to include the desired effects in the modelling with simple commands. The possibility to extract knobs used to correct the machine makes it possible to apply them to the ideal model and observe how the machine would behave without the knob in place.

Figure 1 shows the flow of the online model. The extractor requests the information from a measurement database and from a setting database. It then combines the information and converts it into MAD-X TFS table format, which can be used for the orbit- and β-modelling. All this is then put into a MAD-X description that can be used as is or edited by the user.

EXTRACTOR

In order to create an effective model it is first important to extract all the necessary parameters. There are two groups of parameters that are being extracted. The first group consists of settings, such as the optics in use and settings of selected knobs. These settings are extracted from the LHC Software

Architecture (LSA), which is a high-level layer of the LHC control system [2]. In the LHC, knobs normally refer to a set of magnets that are being changed to adapt, for example, the crossing angles or the transverse coupling. The second group is measurement parameters, such as the tune, energy and orbit. These parameters are stored in a measurement database and are extracted using a Java API. Since different studies need different input it is important to keep the software flexible enough so that the user can include any combination of desired effects. The corrections knobs are in general applied to compensate for the imperfections in order to bring the real machine closer to the ideal one. This also means that extracting all settings of the machine and plugging them into the model will not result in a better model. For example, extracting the settings of all the quadrupoles in the LHC will result in a less accurate β-modelling since the introduced changes are applied to be closer to the nominal model. Instead, a different approach is being used to model the β-functions in the machine. During the commissioning of the LHC the β-functions are measured and we can use these values to create a more accurate model. A similar approach is then implemented for the orbit and both are described in this paper.

ORBIT MODELLING

There are different methods of modelling a specific beam orbit in MAD-X. For the LHC online model, virtual orbit corrector magnets are used for this purpose. A virtual orbit corrector magnet works as a real orbit corrector magnet by applying a momentum kick in the horizontal or vertical plane. These magnets are only included in the model lattice, and not in the real machine. In practice, the virtual correctors will collectively reproduce the effects of misaligned quadrupole magnets and other sources of orbit deviation.

Orbits for the two planes are measured in the machine and are made available to the online model through the model extractor. The orbit is then reconstructed by the orbit correction routine in MAD-X and the corrector strength for each virtual corrector is saved. The saved corrector strengths can then be read back by other MAD-X scripts, to obtain the same measured orbit. As long as there are no major orbit changes in the machine the corrector strengths does not need to be recomputed.

The virtual corrector magnets can in principle be placed anywhere inside the model lattice. For the LHC online model there is one virtual corrector magnet placed at each quadrupole magnet. In this scheme, the corrector strengths needed to reconstruct the measured orbit will mainly esti-
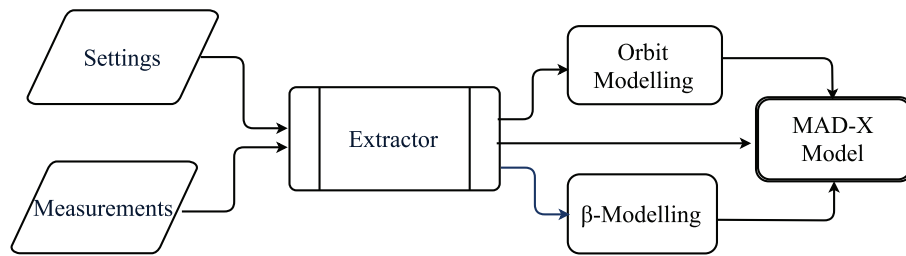
Figure 1: The conceptual flow of the online model.

mate quadrupole magnet misalignment, but also errors of the neighboring main dipoles.

Figure 2 demonstrates the result of reconstructing a measured horizontal orbit. Good results are obtained for the arc sections of the LHC, while less accuracy is obtained for the interaction regions. In part this can be explained by extreme β-function values in these regions as well as less accurate BPM measurements [3]. This can be seen from the erratic behavior of the measured orbit in the upper plot in Figure 2. It is possible to manually disable monitor readings which are believed to be incorrect, in case the monitor has not already been flagged as invalid.

A detailed manual for the virtual corrector scheme implementation in MAD-X, as well as full examples, can be found at the LHC online model web page [4].

BETA MODELLING

The β-matching module is intended to reproduce the measured linear optics. The aim is to create a model where the β-functions are as close as possible to the measured. The measured beta functions are stored in a database. The extractor then retrieves the data when needed for the modelling. In order to model the β-functions it uses thin virtual quadrupoles placed in the middle of real quadrupoles. The strengths of the virtual quadrupoles are calculated using the pseudo-inverted response matrix. The response matrix is created in MAD-X and it contains variations in beta function at each monitor corresponding to a change in the strength of each virtual quadrupole. The method is very similar to what is used to calculate global optics corrections [5]. The accuracy of the method benefits from the newly developed algorithm to reconstruct the β-functions based on N-BPMs [6]. This concept is easily extendable to other types of magnets and could also be used to match for example the transverse coupling using skew quadrupoles.

Typical RMS difference between the obtained model with respect to the measurement is about 0.7% and 0.6% in the horizontal and the vertical plane, respectively. An example of the relative difference between the measured and the matched model is shown in Fig. 3. This is significantly better than the RMS of about 4% between the nominal situation and the measurement. The more precise knowledge of the β-functions are useful both to create a more accurate model
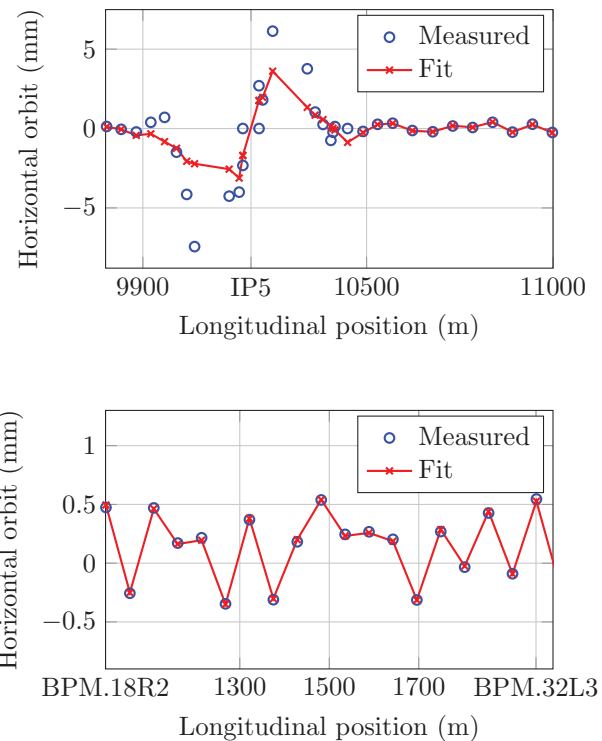

Figure 2: Comparison of the measured and reconstructed orbit for part of one the arcs (below) and around IP5 (above). The x-axis starts from the injection point close to IP2. The beam energy for the measurement was 6.5 TeV and the optics configuration was squeezed optics with a β^* = 80 cm at IP1 and IP5.

to predict any changes but also to directly extrapolate the measurements to other points in the machine.

USER INTERFACE

There are two main ways of invoking the online model. The first one is through a command line tool, which then creates the model based on the input string and a configuration file. However, in order to facilitate studies, a graphical user interface has also been developed. It provides the user with an easy way to create a model of the machine at given
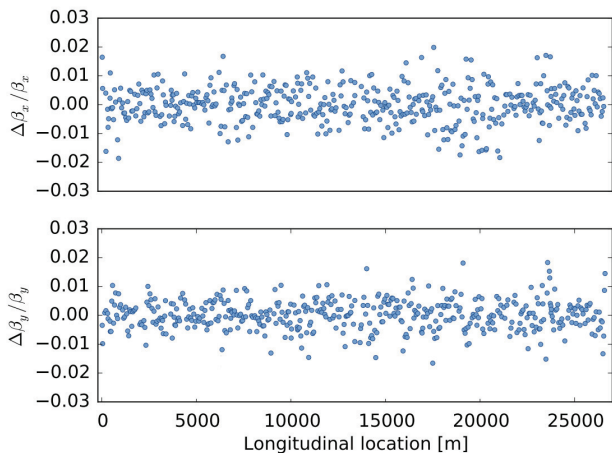
Figure 3: The relative difference between the measured and the matched model. The measurement refers to the optics configuration at flattop in 2015. The x-axis starts from the injection point of Beam 1 close in IP2.
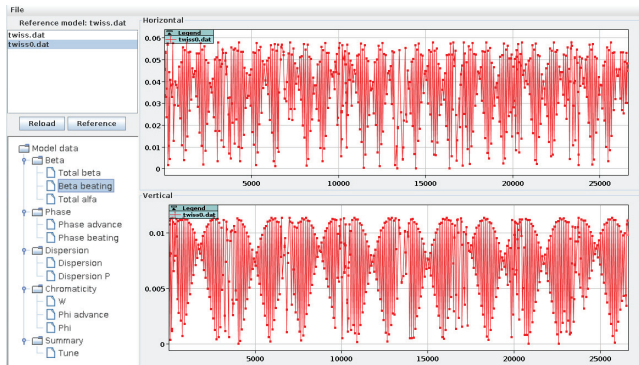

Figure 4: The normalized difference in the β-function between the two models.

time and then include different features, for example orbit matching. The different parameters such as the tunes, β-functions and dispersion are then being displayed and the user can view the differences between a reference model as shown in Fig. 4. When the model is created the user can, for example, vary strengths of magnets and then investigate the impact on the optics. All the MAD-X scripts are output in a folder so they can be run using other scripts to automatize different changes. A detailed description of how to run the GUI and the command line interface can be found in [4].

EXAMPLE STUDY

The online model has been used in several different studies. One of the studies aimed at understanding the influence of the powering of the octupoles on Q' (chromaticity) and Q''. The machine orbit was reconstructed and the offsets of the magnets were taken into account in the prediction. The octupoles were then set to different strength in the model
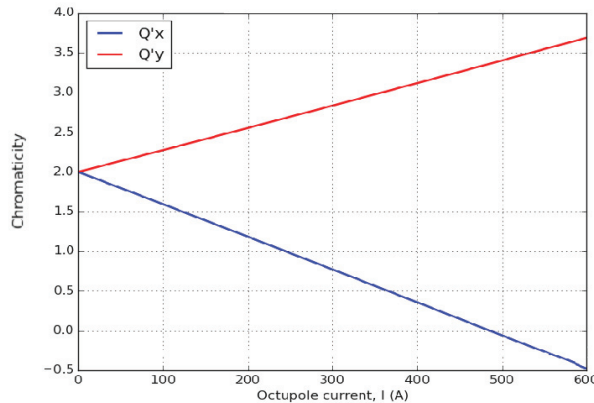

Figure 5: The chromaticity as a function of the powering of the octupoles with the measured orbit reproduced in the model.

and the predicted changes in Q' and Q'' were investigated as shown in Fig. 5 [7].

Another example was during an impedance measurement, that relied on accurate tune determination. During the measurement an orbit change also occurred. The study, with the online model, then aimed to understand if the orbit change together with feed-down could have a large enough effect to cause the observed tune change. The results showed that it was indeed possible and hence, it was not possible to use the measurement to draw conclusions on the impedance.

These are example of typical study which demonstrates the importance of a beam-based model in order to describe the machine more precise and hence interpret the results from a study more accurately.

SUMMARY AND OUTLOOK

The online model has already been used in studies to provide a more accurate description of the machine used to study for example the feed-down on tune and chromaticity. The part of the online model which has been described in this article is part of a larger frame-work of tools. Example of other tools are the aperture meter [8] and the footprint viewer [9]. The possibility to easily extract the settings and measurement from the machine and include them in model creation enables is crucial to create more precise and accurate models. These features will be of increasing importance as the operational parameters of the LHC will entering a more challenging regime.

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