SPS AND LHC TUNE CONTROL STUDIES USING THE "FAST MAP" TOOL

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Abstract

An important issue for LHC operation will be the continuous monitoring of the betatron tunes and chromaticities. Of particular interest for eventual on-line tune and chromaticity control is the question "How do time-varying non-linearities of the LHC magnets (snap-back, etc…) affect these measurements?" In order to answer this question seven years before the date of commissioning, a computer model is required to stand in the place of the real charged particle beam. FAST MAP (FM) is a suite of tools that has been written to facilitate high-speed tracking (using COSY [1] generated maps) and to customize the maps to a sufficiently large number of tuning parameters ("knobs") in addition to the six kinematic variables. FM has been interfaced with a Measurement Front End capable of simulating the measurement of the tune, chromaticity and coupling by a variety of techniques. It is intended to test the validity of these tools by experimental comparison in the SPS before applying them to the LHC. In this article we describe some features of FM and some of its applications to beam diagnostics studies in the SPS and LHC.

1 INTRODUCTION

The injection and acceleration of the LHC proton beams without particle losses and emittance growth requires an accurate control of the beam parameters. For example the value of the betatron tunes need to be controlled to a level of 0.003 and chromaticty to 1 unit. This is a challenging task for an accelerator with superconducting magnets, whose field and field errors will have a large time-dependent variation. It was observed during the field quality measurements on the dipole prototype (MTP1N2) that the multipole field exhibits slow time drift, as the current is kept constant, and a rapid change at the beginning of the energy ramp ("snap-back") [2,3]. Therefore, the magnetic field of the dipole, quadrupole, sextupole and corrector magnets need to be precisely synchronized during the energy ramp in order to achieve the strict requirements on the betatron tune and chromaticity. Indeed, the tolerances are so tight that apart from the standard feedforward techniques and measurements on reference magnets one will be forced to use feedback from beam measurements directly.

The development of this beam-control procedure seven years before LHC commissioning will need a computer model to stand in place of the real particle beam. To allow adequate simulation of the beam behavior during energy ramping, the following requirements were set for the beam model:

- *Fast response*. From measurements of the LHC dipole prototype significant change of the multipole contents is anticipated over several seconds, i.e. more than 10^4 machine turns. Hence tracking over such a number of turns should not last longer than a few minutes.
- *Modelling of chromaticity and/or multipole field components*. To simulate "snap-back" during the beginning of the energy ramp, the multipole components of the elements must be varied during run time. When the lattice is represented by a single map, one possible solution is to enter free parameters into the map to describe the field components. The order of the map has to be at least 6 to include the first term of the octupole field expansion.
- *The Beam to be represented by an ensemble of macro-particles (typically more than 100).* The use of an ensemble comes from the fact that we wish not only to find the centroid motion of the particle beam including decoherence, but also simulate the effect of the measurements on emittance growth.
- *Integration with the off-line beam measurement simulator and with the tool simulating the real time feedback to magnetic elements.*

None of the available tracking programs fulfils all of these requirements. The solution adopted was to write a highly optimized particle tracking code and attendant utilities for managing COSY-generated maps so as to allow many free parameters apart from the kinematic variables. The suite is called FM.

2 DESCRIPTION OF THE FM TOOLS

The solution framework using FM consists of the following steps:

1) Convert SPS and LHC lattices from a MAD 8/9 file format into a FOX file – executable for COSY. This task is accomplished by a *twiss2cosy* conversion utility.
2) Use COSY to obtain a set of the parameterised maps. Memory and performance limitations in COSY make it difficult to work with more than 2 free parameters for a 6^{th} order map. The requirement of at least 12 free parameters ("knobs") means that several

maps have to be produced, each with a maximum of 2 or 3 parameters.

3) Combine all parameterized maps into one table (a map-like object that depends on all 12 or more parameters). This operation is assigned to the *mapmerge* utility. Note that the output file is not a "map" in the strictest mathematical sense unless all cross -coefficients are supplied.
4) The *fmlib* objects are used to read the *mapmerge* output, evaluate parameters in the map, collect coefficients, and to perform the particle tracking.

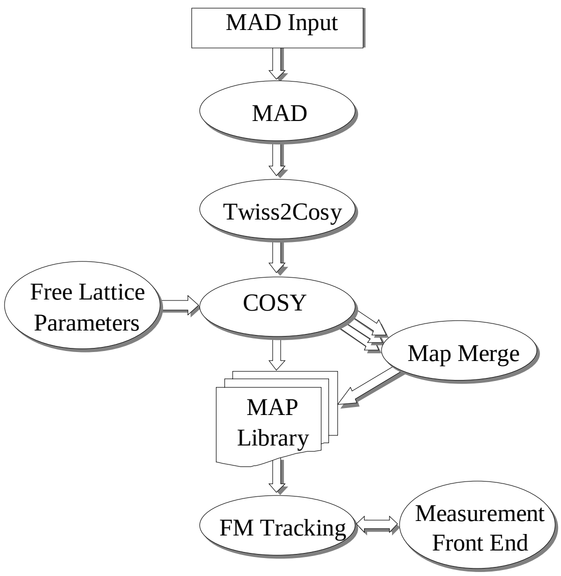

Figure 1: Flow chart of the FM tracking tools

A distinctive feature of the *twiss2cosy* converter is the option to "fold" sequences of elements by detecting and replacing the repetitive parts in the lattice. Factoring out super-periods and repetitive cells, *twiss2cosy* produces the shortest possible representation of the given sequence of elements. The maps for repetitive sub-sequences can then be pre-computed and reused in the final stage of the map calculation for the whole ring. In this case we can expect a large reduction in time needed for COSY to produce a map.

An advantage of tracking with FM rather than COSY arises from the following procedure. Prior to tracking, numerical values are substituted for symbolic parameters and this allow to collect coefficients of like-order kinematic monomials and polynomials; with the effect that the possibly very large map collapses to 6^{th} order in the 6D kinematic variables. These 'reduced' maps can be pre-calculated and stored for later iteration.

3 VERIFICATION OF THE MODEL

A substantial range of verifications of the FM model predictions have been made, including some comparison against experiments on the SPS machine. The first section describes one of the most basic tests that one can do: a comparison of the measured and predicted tune change after a change in the current of the main lattice quadrupoles. As second example, the chromatic dependence of the synchrotron sidebands has been selected, because this demands the correct description of synchrotron motion of the particles. As a last example, the emittance growth after a single-kick beam excitation (for tune measurements) has been chosen, as this demands the tracking of individual particles.

3.1 Tune trims

Figure 3.1 shows the variation of the horizontal betatron tune as the current in one of the main lattice quadrupole strings is changed. The dots show measured values and the triangles the corresponding FM simulations. The agreement is good; the slight discrepancy of the slopes as indicated by the two linear trend lines can be explained by the quadrupolar components of the main dipoles, which are not taken into account in the model.

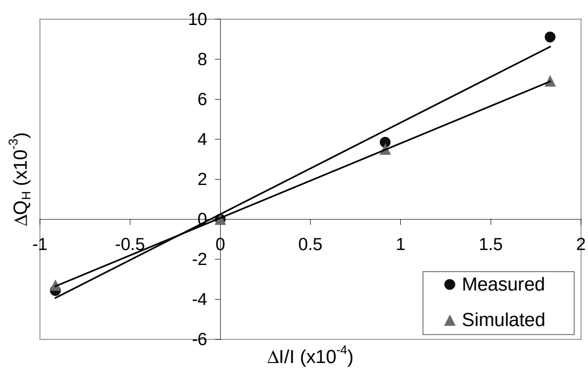

Figure 3.1: Horizontal tune as a function of change in current in the main QD quadrupole string

3.2 Synchrotron Sidebands

The description of synchrotron sidebands demands the correct modeling of longitudinal motion in the tracking and it is of particular interest for tune and chromaticity diagnostics. The amplitude ratio of a synchrotron sideband to the main betatron line is proportional to the chromaticty and hence can been exploited to measure chromaticty. The difficulties of separating the sidebands from the main tune peak in hadron machines (low synchrotron tunes) and the problems of absolute calibration make this rather difficult in practice. More details can be found in [5]. However, these problems are less acute for lepton beams. The following two transverse beam spectra show a measurement example from the positron beams in the SPS for high chromaticty (Fig3.2a), as well as the corresponding FM simulation (Fig3.2b).

The observed spectra are reproduced by the FM simulation. The first sideband and the second (although close to the noise floor in the measurements) are visible in both graphs. Due to the lack of time in preparing this paper, no effort was made to correctly reproduce the

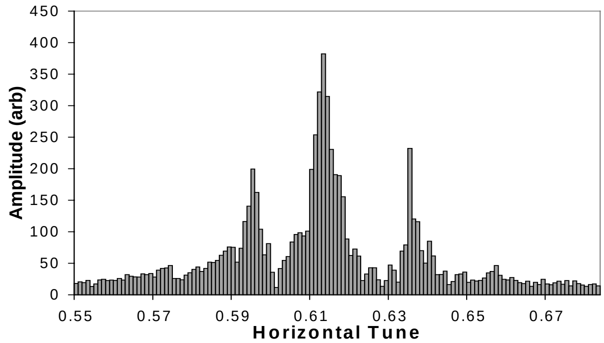

Figure 3.2a: Measured horizontal spectrum of the betatron motion of positrons in SPS

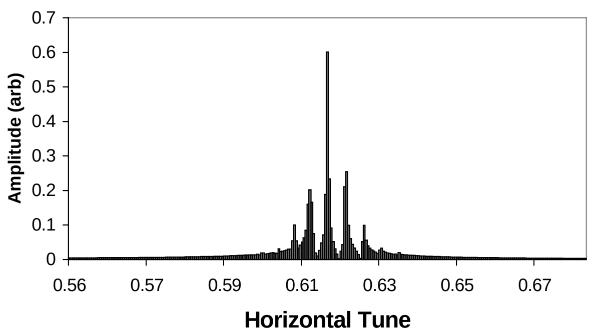

Figure 3.2b: Simulated horizontal betatron spectrum for a comparable chromaticity as in fig 3.2a

synchrotron tune of the positrons. For that reason the sidebands are differently spaced in both graphs.

In order to make a better comparison between the model and the measurements, fig.3.2c summarizes a whole series of measured and simulated spectra. The figure shows the amplitude ratio of the first sideband to the main line as a function of the chromaticty trim. A nice linear behaviour can be seen for the measurements on protons and positrons as well as for the simulations.

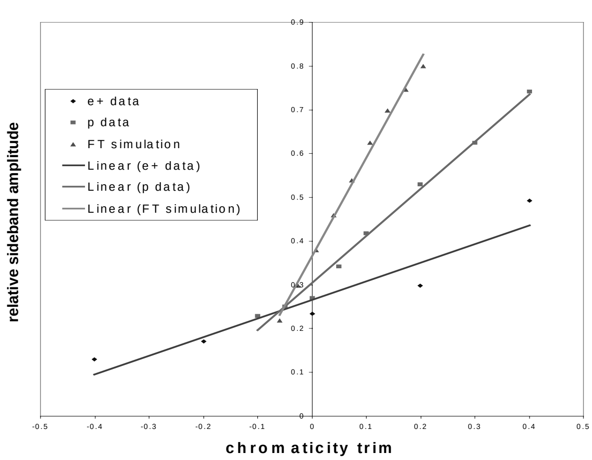

Figure 3.2c relative amplitude of synchrotron sidebands as function of chromaticity trim.

3.3 *Emittance Growth*

As a test of whether the evolution of phase-space distributions are correctly described by the model, the emittance growth after a single kick excitation was simulated, the transverse emittance being computed from the phase space variables of the individually tracked particles. The result is compared to the well-known equations that predict final emittance growth by adding kicks (or errors) and emittance in quadrature. Fig.3.3 shows the result for a simulation of 3 consecutive kicks. The model correctly describes the expected emittance growth (crosses, called "theoretical" in the plot) after some filamentation time.

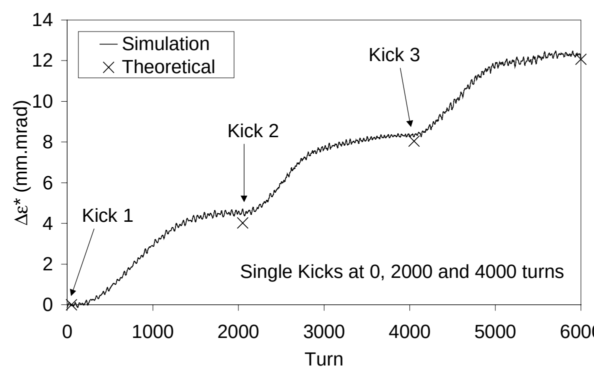

Figure 3.3: Simulated emittance growth after single kick beam excitations such as used for tune measurements.

4 CONCLUSION

With the creation of FM, a powerful tracking tool has been developed that will allow to simulate the response of a particle beam to a variety of control algorithms such as may be used for on-line measurement of tunes and chromaticty. The ability to vary a large number of time-dependent parameters makes the FM tools particularly suited to resolving control issues for machines such as the LHC and RHIC. The model predictions have been successfully verified against theory and experiments at the SPS.

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