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DECOUPLING SCHEMES FOR THE TEVATRON IN THE PRESENCE OF SKEW QUADRUPOLE FIELDS*

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Abstract

Increasing demands for luminosity in existing and future colliders have made both lattice design and error tolerance and correction critical to achieving performance goals. The current state of the Tevatron collider is an example, with a strong skew quadrupole error present in the operational lattice. This work studies the high order performance of the Tevatron and the strong nonlinear behavior introduced when a significant skew quadrupole error is combined with conventional sextupole correction, a behavior still clearly evident after optimal tuning of available skew quadrupole circuits. An optimization study is performed using different skew quadrupole families, and, importantly, local and global correction of the linear skew terms in maps generated by the code COSY. This correction scheme is compared with the present Tevatron operational lattice and corrector configuration.

INTRODUCTION

Increasing the luminosity reach of existing and future colliders demands considered and precise optical design and predictability in operation. Driven by nonlinear fields, "high-order" beam dynamics are generally difficult to control, calculate, and can severely limit a machine's region of stable operation. An approximately linear lattice is desirable for operational simplicity and understanding; it also generally exhibits more robust, broader-range performance. Nonlinear sources arising from field and alignment errors and required correction elements are unavoidable. Successful management of nonlinear sources, however, depends on the linear lattice. Attributes of the linear lattice and relative locations of sources generate interference, constructive or destructive, between the nonlinear terms depending on their periodicity. In a highly effective linear lattice design, the strongest nonlinear amplitudes can be mitigated passively by intelligently exploiting periodicity, phase advance and optimal placement of nonlinear correctors. Such a lattice enhances precision and predictability in the machine optics. Passive cancellation, however, is generally not sufficient to address certain systematics or widespread field errors; active correction in the form of added corrector elements is usually required. The overall lattice approach must be evaluated not only by its tolerance of errors, nonlinearities and natural aberrations, but also by its potential for active correction. Such correction may be "global" in the sense that an error or aberration is corrected over one-turn optics. Global correction is not always adequate to maintain sensitive collider optics. Immediate — or "local" correction — of source terms, particularly if such terms propagate through the delicate optics of the interaction regions, may be an additional requirement for stability and linearity. The case addressed in this work is the current state of the Tevatron collider, where a strong, systematic, skew quadrupole error is present in the operational lattice as a result of a coil shift in the superconducting arc dipoles.

TEVATRON LATTICE AND SIMULATION

With the increasing demands for luminosity, optimal performance must be extracted from the existing Tevatron optics. Local correction of errors and other strong sources of aberrations is necessary to achieve the desired optical performance and luminosity. We have, therefore, initiated a high-order dynamical study of the Tevatron to assess the performance, functionality and potential of the baseline lattice. For this study, we are concerned only with the design Tevatron lattice which we consider to be simply the linear lattice (quadrupoles and dipoles) and the chromatic and feed-down sextupoles combined with the strongest low-order nonlinearities. The strongest nonlinear sources in this lattice are first, the chromatic correction and feed-down sextupoles and, second, the strong sextupole and skew quadrupole error fields found in the arc dipoles. Skew quadrupole errors are very important because they change the linear lattice. This work describes the high-order performance of the Tevatron lattice with emphasis on the coupled and increased nonlinear behavior introduced by the significant skew quadrupole error in combination with conventional sextupole correction, a behavior still clearly evident after optimal tuning of available skew-quadrupole corrector circuits. An optimization study was then performed using the available, single-family skew quadrupole circuit. This optimization was effected by locally and globally correcting the linear skew terms in maps generated by the code COSY INFINITY (COSY) [1]. In the 2004 shutdown, 50% or more of the coil shifts in the dipoles were to be corrected and two schemes were investigated with the above method to determine the best pattern of dipole correction. In both schemes the aim is to apply the technical correction to the skew quadrupole sources in such a way as to allow the single-family circuit available to complete the correction and decoupling of the lattice. The results of the decoupling pattern and correction were highly successful and are reported here.

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Lattice Description

The Tevatron lattice [2] is comprised of 6 arcs and 6 straight sections with interaction regions CDF and D0, occupying two of the straights. The lattice has a simple periodicity of one, but with no reflective symmetry. Even the arcs are not perfectly regular, but remain adequately described by a FODO cell with 72 degrees of phase advance in each plane. The global tunes are 20.585 and 20.575, in the horizontal and vertical, respectively, and clearly not split by an integer as is common in current lattice design. For the simulation, first a high-order Taylor series one-turn map of the Tevatron is generated using the differential algebra code COSY with the baseline lattice described above. The different baseline components of the lattice: the chromatic correction and feed-down families of sextupoles, the skew quadrupole correctors, the strong skew and sextupole systematic errors are implemented in such a way that they could be turned on and off to study individual and correlated effects on performance and effectively troubleshoot the lattice. Initial and updated Tevatron lattice data plus component strengths were obtained from the input deck for the code OptiM [3]. An automated converter [4] has been written to transcribe the OptiM input format to the language of COSY. The converter itself is written in PHP [5], so that it is straightforward to perform online updates or entire conversions of lattices from OptiM to COSY. For now a conversion exists for the following sets of elements: dipoles, dipole kicks, pure and skew quadrupoles, quadrupole kicks, pure and skew sextupoles, sextupole kicks, solenoids and electric separators. The generated code is ready-to-use by COSY. Linear maps without the skew quadrupole correctors and errors and linear parameters such as tunes have been verified and cross-checked with both OptiM and an independent COSY implementation [6]. The checks on the proper conversion of the lattice are as follows. First, beta functions [7] for closed orbit were compared with OptiM. Quantitative comparison showed less than a percent level difference. Slight differences were due to a more realistic implementation of the detector solenoids in COSY.

High-Order Maps and Tracking

Typically an 11th to 15th order map was required for complete convergence of nonlinear effects, but lower orders (7th, for example) provided a quicker check on the direction of results and optimizations. Particles were launched at the CDF interaction point in steps of one sigma (for normalized emittance of $10\pi \ mm \cdot mr$ at injection $\sigma = 1.2 \cdot 10^{-4} \ m$). Particles were tracked in COSY by applying the map repetitively for typically $10,000$ turns. Only the injection optics was being studied. It is important to note that the study is not, per se, a dynamic aperture one for which particles are launched along phase space vectors scaled to the linear injection ellipse and the transmitted transverse phase is mapped. Dynamic aperture studies are not always informative as to beam dynamics. In a predominately linear lattice, tracking along a single vector in one plane of phase space and then the other is sufficient to trace out the matched ellipse. Particles can be simply launched along the x or y axis, for example. We are looking for degradation of linear motion as evidenced by dissolution or distortion of the linear invariant ellipses. Since the current study is directed at optimizing linear performance, this is the approach used for tracking and the criterion for improvement. The tracking results presented in this and subsequent sections are obtained for $10,000$ turns with points plotted every 10th turn, and the scales are $2.4 \cdot 10^{-3} \ m$ for x, y-axes and $4.0 \cdot 10^{-3}$ for a, b-axes ($a = p_x/p_0$, $b = p_y/p_0$). Tracking is performed with a symplectification algorithm written by Bela Erdelyi [8] and calculation order 7. All the particles are launched either along x or y axis, which is explicitly mentioned in each figure caption.

Skew Quadrupole Errors and Correction

Each of the Tevatron arcs has 15 FODO cells with skew quadrupole correctors in every odd-numbered cell, which means one corrector every two FODO cells. The skew correctors are placed next to horizontally-focusing quadrupoles only. There are also 8 independent correctors in the straight sections which were used for further global correction. The Tevatron lattice was initially tracked

- without the quadrupole error fields and then
- with them in every arc dipole

to assess the impact on the linear performance and dynamic aperture. The skew quadrupole correctors were then turned on to the optimal strength for correction to evaluate their effectiveness (Fig.1).

An obvious conclusion is that one family of skew quadrupole correctors is not sufficient to correct the coupling effect from a systematic skew quadrupole error in all the dipoles along the ring. However, during the 2004 shutdown more than 50% of the coil shifts were repaired which eliminated the strong skew quadrupole error field in specific, “fixed” dipoles. With certain correction patterns, it is possible for one circuit of skew quadrupole correctors to eliminate coupling from the arcs generated by the remaining “unfixed” dipoles. One object of this study was to discover both the optimal dipole pattern for error correction and the new setting for the skew quadrupole correctors. Since an optimization where all the strengths of the skew correctors are different is not practical (all the correctors in the arcs have the same power supply), a single strength is applied to all the arc correctors. The 8 correctors in straights are allowed to have different strengths. The optimization process itself consists of two steps. First, the optimization of each arc is performed using skew quadrupole corrector strengths as control parameters. This optimization would be optimal if no skew quadrupole components existed in the straight sections of the Tevatron, but there are skew errors and correctors for the interaction regions. Because of these components and the residual skew terms from the arcs

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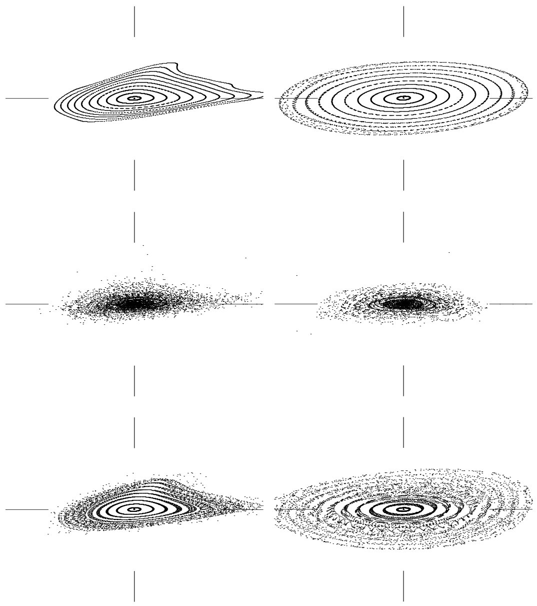

Figure 1: x-plane and y-plane phase portraits before the optimization, particles launched along x- and y-axis respectively. The phase portraits include: a) all sextupole fields in addition to quadrupoles and dipoles, and NO skew quadrupole errors in dipoles, b) all sextupole fields in addition to quadrupoles and dipoles, and all the skew quadrupole errors in dipoles, c) all sextupole fields in addition to quadrupoles and dipoles, skew quadrupole errors in dipoles and also skew quadrupole corrector fields set to optimal values.

since the arcs are not perfectly regular, the skew terms of the one-turn transfer map have nonzero skew quadrupole terms which require correction even when the arcs are all optimally decoupled. To remove this smaller, final stage of coupling requires a second step to the optimization. In four of the six straight sections there exist eight skew quadrupole correctors and the strengths of these correctors were used to finish the skew-quadrupole term cancellation in the one-turn map. Two optimization schemes were considered which differed in the dipole pattern used for correcting the skew quadrupole error. One scheme “fixed” the two dipoles on either side of the vertically focusing quadrupole and the other “fixed” all 8 dipoles in arc cells missing a corrector. Although the two schemes were similar in performance, the latter, under ideal conditions, produced the most linear performance and is shown below. It was also discovered that the optimal correction occurred when specific skew quadrupole correctors were not used — using only 5 instead of 7 correctors/arc produced the best decoupling. Although these portraits are for the closed orbit of the Tevatron, simulations and tracking were also performed for beam launched on the helices and the results and conclusions remain the same.

Fig.2 shows the phase portraits after optimization for optimal correction pattern using all arc correctors, and optimal correction using only 5 correctors/arc.

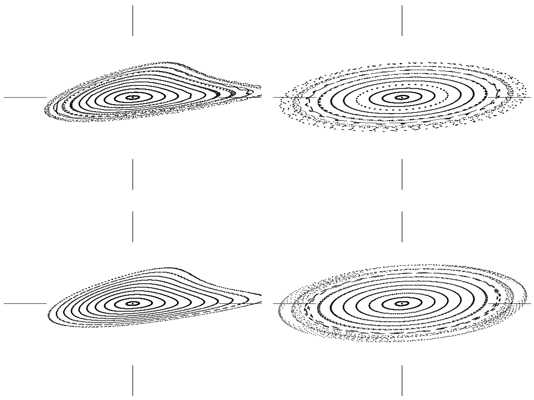

Figure 2: x-plane and y-plane phase portraits after the optimization, particles launched along x- and y-axis respectively. 7 (upper pair) and 5 (lower pair) skew quadrupole correctors in each arc, 50% of the dipole errors fixed.

CONCLUSIONS

The methodology described for investigating and correcting the Tevatron lattice was highly successful in discriminating between and recommending approaches to decoupling the lattice in the presence of a strong, systematic skew quadrupole error. The Tevatron lattice, overall, demonstrates strong high-order effects which appear to be accurately represented in the maps generated by COSY. Further studies will incorporate more, higher-order field errors and simulation comparisons of operational procedures such as minimal tune split vs. minimizing linear skew terms in the map described here.

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