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Study and optimal correction of a systematic skew quadrupole field in the Tevatron

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Abstract

Increasing demands for luminosity in existing and future colliders have made 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 INFINITY [M. Berz, COSY INFINITY version 8.1 user's guide and reference manual, Department of Physics and Astronomy MSUHEP-20704, Michigan State University (2002). URL http://cosy.pa.msu.edu/cosymanu/index.html]. Two correction schemes with one family locally correcting each arc and eight independent correctors in the straight sections for global correction are proposed and shown to dramatically improve linearity and performance of the baseline Tevatron lattice.
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1. Introduction

Increasing the luminosity reach of existing and future colliders demand 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 the 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

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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. A 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.

With 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 baseline Tevatron lattice which we consider to be simply the linear lattice (quadrupoles and dipoles) combined with the strongest low-order nonlinearities. The strongest sources of nonlinearities are first, the chromatic correction and feed-down sextupoles and, second, 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 nonlinear 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 circuits. An optimization study is then performed using available skew quadrupole circuits, and, importantly, local and global correction of the linear skew terms in maps generated by the code COSY INFINITY (COSY) [1].

Two correction schemes with one skew quadrupole family locally correcting each arc and eight independent correctors in the straight sections for global correction proved themselves to give the best results and dramatically improve the linear performance of the baseline Tevatron lattice. In both schemes, the source of the skew error is corrected in such a way as to allow the single-family circuit available to complete the correction and decoupling of the base lattice, which is technically achieved by fixing the coil shift in part of the Tevatron dipoles.

2. Tevatron 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° 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.

3. Lattice data and method

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 has been written to transcribe the OptiM input format to the language of COSY [4]. 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.

4. Checks of the linear lattice

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 the percent level difference. Slight differences are due to a more realistic implementation of the detector solenoids in COSY.

5. Simulation details and tracking results

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 10π at injection $\sigma = 1.2 \times 10^{-4}\,\mathrm{m}$). 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

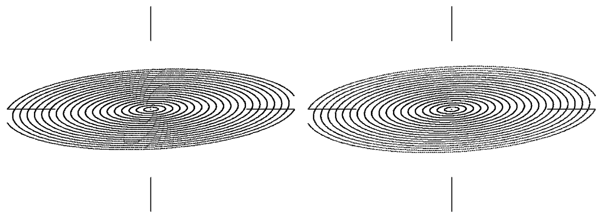

Fig. 1. x- and y-plane phase portraits, only dipoles and pure quadrupoles active, particles launched along x- and y-axis respectively.

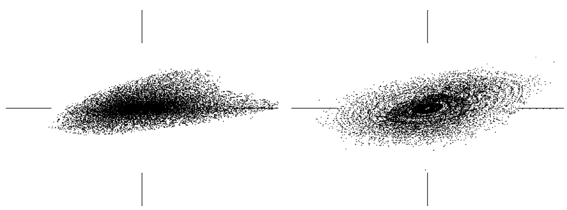

Fig. 2. x- and y-plane phase portraits before the optimization, particles launched along x- and y-axis, respectively. The phase portraits include all sextupole and skew quadrupole fields (correctors plus errors) in addition to quadrupoles and dipoles where 15% of the skew quadrupole errors have been removed in specific dipoles.

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 2.4×10^{-3} m for x, y axis and 4.0×10^{-3} for a, b axis ($a = p_x/p_0$, $b = p_y/p_0$). Tracking is performed with a symplectification algorithm written by Bela Erdélyi [8–11] and calculation order 7. All the particles are launched either along x- or y-axis, which is explicitly mentioned in each figure caption. To start comparing the impacts of different sets of nonlinear elements, in Fig. 1 phase portraits for linear motion are shown. This includes only pure dipoles and pure quadrupoles.

According to the status of the Tevatron before August 2004, With 15% of the skew quadrupole errors removed in selected dipoles, the otherwise unchanged lattice shows significantly reduced stability (Fig. 2). The regular structures disappear and most of the particles can be considered lost in just 10,000 turns. These phase portraits can be considered a starting point of the study of different schemes of the skew quadrupole correction.

6. Skew quadrupole circuits optimization proposals

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.

One family of skew quadrupole correctors is not sufficient to correct all the skew quadrupole errors in dipoles along the ring. But during the next shutdown approximately 50% of the coil shift errors in dipoles can be fixed and in this case one circuit of skew quadrupole correctors is capable of removing the coupling in the arcs. The problem here is to discover both the optimal dipole pattern for error correction and the new strength for the skew quadrupole correctors.

An optimization where all the strengths of the skew correctors are different is not practical. All the correctors in each arc have the same power supply, so it is more realistic to use one strength for all the correctors arc-wise or even ring-wise.

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 close to 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 since the arcs are not perfectly regular, the skew terms of the one-turn transfer map has nonzero skew quadrupole terms which require correction also. 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. The first scheme, proposed by us, attempts the elimination of the skew quadrupole error source predominately in the vertical plane by fixing the two dipoles flanking each vertically focusing arc quadrupole. With one degree of freedom corrected, the remaining predominately horizontal sources can be corrected with the existing single family of skew quadrupole correctors. The layout for scheme I is shown in Fig. 3. One arc of the Tevatron is shown and the others are similar. The dipoles

Sector E scheme I

FODO 1	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 2	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 3	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 4	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 5	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 6	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 7	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 8	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 9	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 10	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 11	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 12	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 13	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX
FODO 14	D*2	FQ		D*2	D*2 FIX	DQ	D*2 FIX
FODO 15	D*2	FQ	SQC	D*2	D*2 FIX	DQ	D*2 FIX

Fig. 3. Correction scheme I, the skew quadrupole error is removed in dipoles in each cell surrounding the defocusing quadrupole.

with skew quadrupole errors are marked with the "D ∗ 2" symbol, fixed dipoles—with the "D ∗ 2 FIX" symbol. The vertically focusing main quadrupole is marked with "DQ" as it is defocusing in the horizontal plane.

The results of the two-stage optimization are shown in Fig. 4. Phase portraits show much more stability, though this scheme is not perfect due to the deviation from completely periodicity in the arcs. However, this scheme was also found to be the most robust to any lattice alterations than the second one which is described next.

The second approach proposed by Michael Syphers [12] is to correct the skew quadrupole errors in each FODO cell missing a skew quadrupole corrector. This scheme was further improved upon by removing specific correctors from the single family to provide more consistent correction in each arc as a function of fractional phase advance. The underlying idea is to correct the error locally at the source and remove it from cells without local correction. This scheme gives improved performance, particularly using one corrector strength across all arcs. Phase portraits for scheme II are shown in Fig. 5. The layout for the scheme is given in Fig. 6. Skew quadrupole errors reside in odd cells with skew quadrupole correctors marked with "SQC". Removing part of the correctors improved performance further and these removed correctors are marked with "SQC RMV".

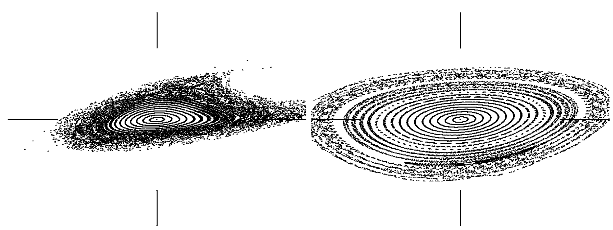

Fig. 4. x- and y-plane phase portraits after the optimization with 50% skew quadrupole errors in dipoles, errors fixed around each defocusing quadrupole, particles launched along x- and y-axis, respectively.

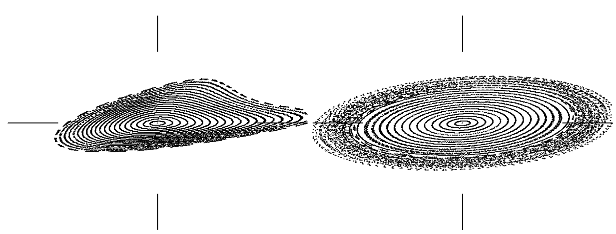

Fig. 5. x- and y-plane phase portrait after the optimization with the skew quadrupole errors removed in the two dipoles flanking each horizontally defocusing quadrupole, particles launched along x- and y-axis, respectively.

Sector E scheme II

FODO 1	D*2	FQ	SQC RMV	D*2	D*2	DQ	D*2
FODO 2	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 3	D*2	FQ	SQC RMV	D*2	D*2	DQ	D*2
FODO 4	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 5	D*2	FQ	SQC	D*2	D*2	DQ	D*2
FODO 6	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 7	D*2	FQ	SQC	D*2	D*2	DQ	D*2
FODO 8	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 9	D*2	FQ	SQC	D*2	D*2	DQ	D*2
FODO 10	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 11	D*2	FQ	SQC	D*2	D*2	DQ	D*2
FODO 12	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 13	D*2	FQ	SQC	D*2	D*2	DQ	D*2
FODO 14	D*2 FIX	FQ		D*2 FIX	D*2 FIX	DQ	D*2 FIX
FODO 15	D*2	FQ	SQC RMV	D*2	D*2	DQ	D*2

Fig. 6. Correction scheme II, skew quadrupole errors in dipoles fixed in each even cell.

7. Conclusions

With all the skew quadrupole errors in dipoles, one circuit of skew quadrupole correctors is not sufficient or requires moving correctors, which is disruptive and expensive. With half of the errors fixed in the dipoles, one set is sufficient to achieve far reaching correction, and with all correctors in the ring set to equal strengths. One of these two schemes is to be implemented during the Tevatron shutdown in August 2004.

The code used, COSY INFINITY allowed tracking to be performed for a very large number of revolutions in a very short time. For example, the whole cycle of calculations, including one-turn transfer map calculation, skew quadrupole correctors circuits optimization and 10,000 revolution high-order (7th order) tracking, runs for 5–10 min on Intel Celeron 1.5 GHz with 256 Mb of RAM. For 11th order, the same task requires 8–12 h. However, 7th order was sufficient to judge improvements and optimization in preparation for the longer, final simulations.

With the skew quadrupole corrector circuits optimized and the dynamics uncoupled, the next study step might be to address the sextupole families and optimization of conflicts between the chromaticity and feed-down sextupoles which was also observed in this study.

Further study should also address possible effects of fringe fields. At this point, such simulations are not easily possible since detailed shapes of fringe field fall-off are not readily available.

Also, in the future normal form methods [13] and methods of control theory [14] might be employed for solving such problems. Normal form methods are effective for long-term stability study, and variational methods along with automatic differentiation algorithms implemented in COSY make it easy to study the behavior of the sets of trajectories of the perturbed motion with respect to the reference particle dynamics. This perturbed motion is then minimized using control theory techniques.

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