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Introduction

It is now generally recognized that a large roll, $\approx$ 6-7mr, in a triplet low-β quadrupole,which couples the horizontal and vertical motion of the beam, can significantly reduce the luminosity and impact the operation of the Tevatron. The question then arises, what is the effect of the small rolls of the low-β quadrupoles on the luminosity. We will consider random rolls with a σ=1,2 and 4mr which can be expected due to errors in the surveys, or changes in alignment after the survey. In the actual operation of the Tevatron we attempt to correct for the coupling and so this study will consider correction schemes and will compare the luminosity, after correction, with a configuration with no rolls.

Method and Results

To understand the impact that small ($\sigma = 1mr$) random rolls of the low-β quadrupoles have on the luminosity of the Tevatron, 100 distributions of

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gaussian distributed rolls for the 12 low-β quadrupoles in the triplet (6 at B0 and 6 at D0) were generated. These rolls couple the horizontal and vertical motion. Each of these 100 configurations of the rolls, or cases, corresponds to a different possible model lattice for the Tevatron.

The model used in the calculations also includes the measured high order multipoles of the magnets in the Tevatron as well as the various corrector circuits. The circuits of concern in this analysis are T:QF, T:QD, T:SF, T:SD, T:SQ0, T:SQA0, T:SQB0, and T:SQD0.

For use as a reference, calculations were made on a lattice without the rolls in the low-β quadrupoles but with the skew quadrupole (and other higher multipoles) of the lattice magnets. For this version of the model, as for all the other cases with rolled low-β quadrupoles, the tunes were adjusted to their nominal values. To do so required reducing the effect of the coupling and was accomplished using the normal tuning circuits, T:QF and T:QD, the skew quadrupole circuit in the lattice, T:SQ0, and the correctors at the end of the straight sections at A0 (T:SQA0), B0 (T:SQB0) and D0 (T:SQD0). The results of this calculation will be referred to as the nominal case to which the other configurations are compared in the following discussion.

In a coupled machine the normal lattice functions should not be used to calculate the area of the beams at the interaction point. Instead the *covariance matrix* calculated from the transfer matrix (the single turn map) should be used.[1] To go from the covariance matrix to an area, a knowledge of the emittance (the ϵ_k in the referenced paper) is needed. To calculate the emittances it was assumed that the beam had, for all the cases, the same fixed size at the injection point, E0.

Normally, when confronted with coupling in the Tevatron, an attempt is made to bring the tunes as close as possible, at the desired values of tunes, to each other by adjusting the strengths of the skew quadrupole circuits. In the calculations we sought to emulate this procedure for each of the configurations for the quadrupole rolls.[2] The tunes were brought together[3] by adjust-

[1]The procedure is described in FERMILAB-Conf95/097 *Calculating Luminosity for a Coupled Tevatron Lattice* by J.A. Holt, M.A. Martens, L. Michelotti, and G. Goderre (May 1995). Helpful discussions, with Leo Michelotti, on that paper are gratefully acknowledged.

[2]Not all of the generated configurations corresponded to stable configurations. If the constructed configuration was not stable it was abandoned.

[3]Considerations of numerical precision using the method described in the paper by Holt et. al. required that for this analysis that the tunes be separated by 0.001

ing the strengths of the tuning quadrupoles and the skew quadrupole circuits T:SQA0, T:SQB0 and T:SQD0. MINUIT was used to find the strengths of these correction elements.

Once the solutions for the correction elements were found it was then possible to calculate, making use of the condition of a fixed size of the beam at E0, the area of the beam at the interaction point.

Figure 1 shows the distribution of the ratio of the areas at the intersection points, B0 and D0, relative to the nominal case, for each of the configurations. Generally the coupling increases the area at the IP. In most cases the increase is small, $<20\%$. The average reduction in the luminosity is $\approx 10\%$. In some cases however, the rotations can reduce the luminosity by more than a factor of 1.5. The effect, on average, is similar at B0 and D0.

A second set of solutions for the strengths of the tuning elements was found by, in addition to minimizing the tune difference, minimizing the ratio of the *rms* orbit change in the crossed plane to the *rms* of the orbit change in the kick plane, due to bumps from the correction dipoles at HE11, VE11, HE13, and VE14. The sum of the ratios from the four kicks, along with the tunes, is used as a measure of fit quality. Again MINUIT was used to find the solutions. Figure 2 shows the ratio of the area at B0 and D0 relative to the nominal case for these new solutions for the strengths in the correction elements.

The new solutions show a significantly reduced crossed plane amplitude (figure 3)[4]. Adding this constraint, in addition to fitting to the tunes, allows MINUIT to find a solution in a greater number of cases. On the other hand minimizing the crossed plane amplitude has only a small effect on the average luminosity (figure 2). Thus I conclude that minimizing the tune difference using the skew quadrupoles at the ends of the IR, at least in the case where the rotations of the low-β quads are small and random, provides a sufficient correction for the coupling and that the effect of these rotations on the luminosity is modest.

These calculations have been repeated with the σ of the rolls in the low-β quadrupoles increased from $1mr$ to $2mr$ and to $4mr$.

With σ increased to $2mr$ the number of good solutions is about half of what it was with a σ of $1mr$. The average luminosity for these solutions is

[4]The amplitude in the crossed plane is now only 1-3% of the amplitude in the kick plane for the different kicks.

only $\approx$20% larger than the nominal case compared to an increase of $\approx$ 10% when σ was $1mr$.

The decrease in luminosity is, in my opinion, significant, but what I do think is more important is the decrease in the number of good solutions found with MINUIT. Tuning the Tevatron in the control room is quite different from tuning a model with MINUIT, but I suspect that when MINUIT finds it difficult to arrive at a solution it will be harder to find a solution in the control room.

Increasing the σ of the rolls to $4mr$ results in MINUIT being able to find a solution in less than 10% of the cases and those solutions show an increase in the area at the intersection points of $\approx$50%.

In both of these cases fitting to the closed orbits as well as the tunes has only a minimal effect on the luminosity and seems to be unimportant as a tool in increasing the luminosity.

I would conclude that rolls of the low-β quadrupoles with a σ of $1mr$ are acceptable and produce tolerable decreases in luminosity. If the σ of the rolls is $2mr$ or larger the tuning becomes more difficult and the luminosity is reduced significantly.

The skew quadrupole correction at B0 and D0 consists of two elements, one at each end of the interaction region. In the past the elements have been connected in series. For the next run each of the skew quadrupole correction elements at B0 will be independently powered. It may be, in the future, that the elements at D0 may similarly be independently powered. The fitting described above has been repeated with the possible new configuration of correction elements in which both B0 and D0 skew correction elements are independently powered. The same set of rotations used above was also used here.

The results from these calculations, with independent correction skew quads, (figure 4) are essentially identical to the results from the calculations (figure 1), where the correction skew quads were connected in series. The correction scheme used last run would suffice in the correction of small, random, rolls of the low-β quadrupoles.

Special Case

The beginning of collider Run IB was made difficult by the rolled Q2 downstream of B0[5]. The result of that analysis of the problem was a model for the Tevatron found by fitting the measured changes in the closed orbit in response to dipole bumps. Using the methodology of this note, the calculated luminosity was reduced to $\approx$60% of the nominal luminosity. Minimizing the crossed plane amplitudes using the skew quad correctors, with the same roll for the Q2, should, according to the calculations, have resulted in an increase in the Tevatron luminosity at B0 to 85% of the nominal luminosity. The calculated luminosity at D0 was not affected by either the rolled Q2 or by the solution found using the crossed plane amplitudes.

The luminosity calculated using the model obtained from fitting the data after the low-β quadrupoles were aligned in Sept. 1994 is the same as the nominal luminosity. These results are in substantial agreement with the results, presented in TM1916, of the effect on the luminosity due to the rolled Q2.

Tracking

It is possible, by tracking a distribution of particles, to compute the size of the beam at any point of the lattice. When changes are made to the lattice, such as the rolls in the low-β quadrupoles discussed before, it is possible to compare the size of the beam at e.g. the interaction points at B0 and D0, before and after the change.

The tuning elements were adjusted as described above, first to bring the tunes together, and then to minimize the *rms* orbit change in the crossed plane. The particles were tracked for 100 turns and the size of the beam at B0 and D0 was calculated. The ratio of the size with the nominal case, i.e. the case with no rotations, for each of the configurations was computed and histogrammed in figure 5. The results are virtually identical with those obtained using the normal form methodology. Agreement is certainly expected and disagreement would cast doubt on the results. The agreement is therefore reassuring.

[5] A discussion of my analysis of that problem can be found in TM1916

Summary

Small random rotations (rotations with a $\sigma = 1mr$) of the low-β quadrupoles about the beam direction do not result in a significant reduction in the luminosity when the tunes are brought together. Reducing the crossed plane amplitude due to dipole bumps does not, in general, result in an improvement in the luminosity. The correction scheme used in the last collider run, with the skew correctors at the end of the interaction regions appears adequate both to correct the tune splitting and the crossed plane amplitudes.

The calculations where the rotations had a $\sigma \geq 2mr$ resulted in a decreased luminosity.

In the case where we had a single large rolled Q2 downstream of B0 minimizing the the crossed plane amplitudes resulted in a solution with improved luminosity.

Tracking and normal form methodologies give consistent results.