

# Feasibility Study of Beam-Beam Compensation in the Tevatron with Wires

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## Abstract

We explore the possibility of compensating long-range beam-beam interactions in the Tevatron by current carrying wires. Compensation strategies depend on whether the compensation is done close to the interaction or non-locally, on the aspect ratio of the strong beam and on other details. Strategies for each case have been developed and applied to the Tevatron. We discuss the results of these strategies at injection and collision energy.

## INTRODUCTION

The idea of compensating the effects of long-range beam-beam interactions by current carrying wires was originally proposed for the LHC [1]. Machine studies performed at the CERN SPS in 2004 and 2005 have tested the effects of a single wire and of two wires on a single beam [2, 3]. While these results are not yet conclusive, they do suggest that wires could be helpful in reducing beam losses in the LHC. It is a natural extension to apply the idea of using wires to compensate the long-range beam-beam interactions in the Tevatron where they are known to cause beam loss at all stages of the operational cycle. The LHC is well suited to this compensation principle since all the long-range interactions on one side of an interaction region are at nearly the same betatron phase. In the Tevatron on the other hand, the long-range interactions occur all around the ring and at very different phases. Given these differences in the the optics and dynamics of the long-range interactions, we expect the compensation strategies to be significantly more complex in the Tevatron than in the LHC.

## LOCAL COMPENSATION OF ROUND BEAMS

The compensation principle is based on the observation that the field of a long straight current carrying wire has the right symmetry and dependence on distance to cancel the field of a round beam at large distances from the beam. In the region closer to the core of the beam where the exponential part of the beam-beam force is important, the cancellation will not be exact. Figure 1 compares the kicks from a round beam with that of a round wire. At separations larger than  $3\sigma$ , the field profiles match very closely - to better than 1%.

To test the compensation principle for a near ideal case in the Tevatron, we chose a parasitic interaction at top energy where the beams are nearly round. The separation at this parasitic was increased to  $10\sigma$ . The wire was placed at the same longitudinal location and at the same transverse distance from the anti-proton beam as the proton beam on the other side of the anti-proton beam. We used several

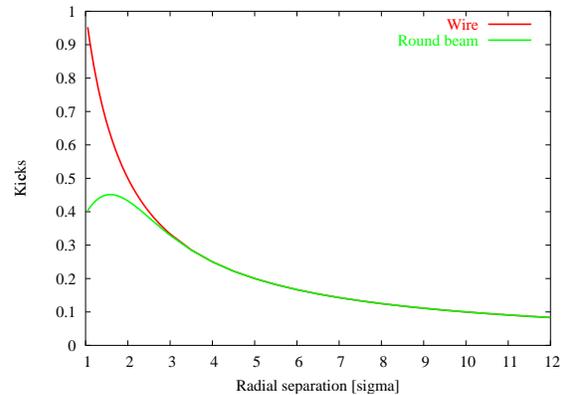


Figure 1: Kicks from a round beam compared to the kick of a round wire as a function of distance. At distances larger than  $3\sigma$ , the kicks agree to better than 1%.

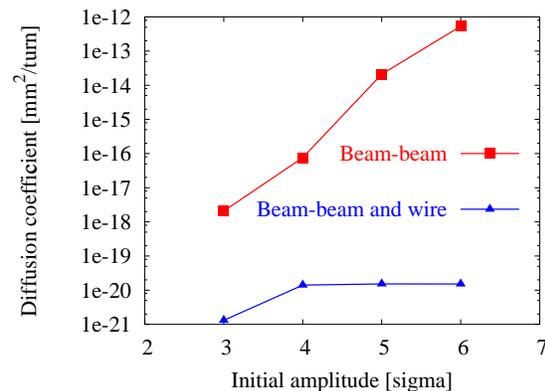


Figure 2: Diffusion coefficients for the local correction of a parasitic interaction where the beams are round and the separation approximately  $10\sigma$ .

measures to calculate the impact of the wire on the anti-protons. One measure, shown in Figure 2, were diffusion coefficients at several transverse amplitudes with and without the wire. These coefficients were calculated with multi-particle tracking using the weak-strong code BBSIM [4]. Fig. 2 shows that diffusion coefficients for all amplitudes up to  $6\sigma$  are practically vanishing with the wire in place. The simulations confirmed what we expected from theory. While this simulation demonstrated the compensation principle at work, it is not very practical for the Tevatron for at least two reasons: (i) beams are not round at most locations and (ii) wires cannot be placed at every location of a beam-beam interaction.

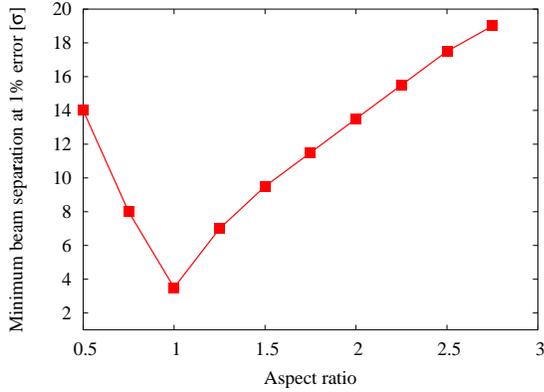


Figure 3: Minimum beam separation required to match a  $1/r$  field as a function of the aspect ratio of an elliptical beam.

## LOCAL COMPENSATION OF ELLIPTICAL BEAMS

The aspect ratios in the Tevatron range between 0.25 - 3.5 with the extremes occurring at low beta at the nearest parasitics around B0 and D0. The difference between the kicks due to a very elliptical beam and a round wire can be substantial. Figure 3 shows the minimum distance from an elliptical beam at which its field matches a  $1/r$  field to within 1%. If the beam sizes in the two planes differ by more than a factor of 2, then the minimum beam separation exceeds  $14\sigma$ . However the range of beam separations at all the parasitics lies between  $5.5$  to  $12\sigma$  and the field of the strong beam at several parasitics cannot be well approximated by a round wire.

We therefore examined alternative compensation strategies. Instead of directly compensating the field, we can compensate some of the effects due to the field. For example, tune shift compensation, nonlinear map minimization, resonance compensation, and numerical optimization were examined. After detailed exploration of these strategies [5], we concluded that the best strategy for local correction of elliptic beam-beam kicks with round wires is to place the wire to ensure that the kicks have the right orientation, and adjust the current to match their magnitudes. However this strategy did not reduce diffusion with the wire placed at the location of the parasitic.

We next looked at a different wire cross-section to better match the field. Elliptic cylindrical wires are a very good approximation of the elliptic Gaussian beam-beam kicks outside the core of the beam. As seen in Figure 4, the relative error at distances larger than  $3\sigma$  from the strong beam centroid are smaller than 2% and decrease monotonically at larger distances. The transverse position and current of the elliptical wire are the same as in the round beam case, and the transverse size of the wire is related to the rms Gaussian beam sizes [5]. Detailed simulations with these elliptic wires have not yet been performed.

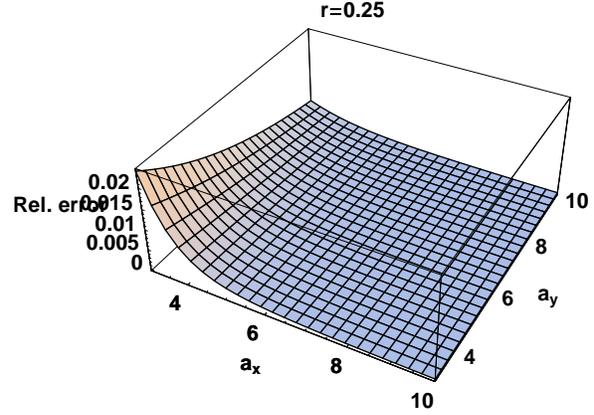


Figure 4: The relative error between an elliptical wire and elliptic beam-beam kicks as a function of amplitude outside the core for small aspect ratio.

## NON-LOCAL COMPENSATION

If the wire is not at the same location as the beam-beam interaction, then simply cancelling the kick at a distant location is the wrong strategy. This can increase the phase space distortion depending on the phase advance between the beam-beam interaction and the wire. Instead we could use the wire to restore the phase space trajectories back to their original paths in the absence of the beam-beam interaction. If a single parasitic interaction with a round beam is compensated by a wire at some distance, then from the above principle it follows that the three conditions for the compensation to be exact for all particles are [5]

$$\psi_x = m_x \pi, \quad \psi_y = m_y \pi, \quad \frac{\beta_{y,w}}{\beta_{x,w}} = \frac{\beta_{y,b}}{\beta_{x,b}}, \quad I_w l = ecN_p \quad (1)$$

The first condition states that the compensation can only be effective if the wire is at an integer multiple of  $\pi$  away in phase in both planes. This is a very restrictive condition. The second condition requires that the beta functions at the wire have to be in the same ratio as at the beam-beam interaction. The third condition determines the integrated wire strength in terms of the bunch charge  $N_p$ .

If multiple parasitics are to be compensated by a single wire, then the conditions for the wire location can also be found by minimizing the phase space distortion [5]. However the compensation cannot be exact for all particles in the bunch but can only be satisfied in an average sense by averaging the kicks over the anti-proton bunch distribution.

We tested non-local compensation in 3 different cases: i) compensating the nearest parasitics around B0 by a single wire, ii) compensating the nearest parasitics around D0 by a single wire and iii) compensating all 4 of these nearest parasitics by 2 wires. The placement of the wires is complicated by the fact that longitudinal locations of the  $\pi$  phase advances in each plane corresponds to different positions in the Tevatron. Calculations were done with the wire placed at locations where the phase advance from the parasitics

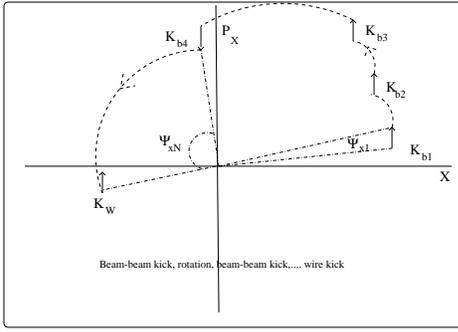


Figure 5: Phase space point following several beam-beam kicks, phase rotation between these kicks and ending up at a wire.

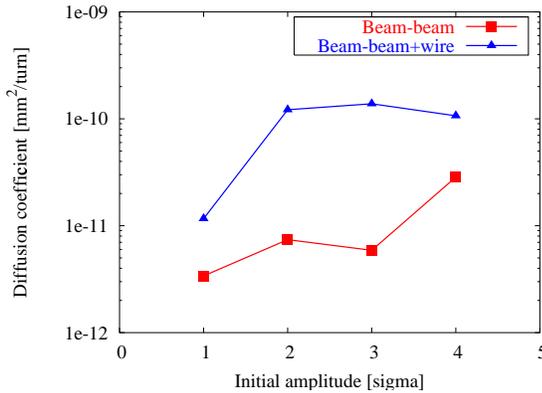


Figure 6: Horizontal diffusion coefficients of the two nearest parasitics to B0, without wire and with wire placed to cancel the average kick felt by the anti-proton beam.

was  $\pi$  in the horizontal plane, vertical plane and averaged between the two planes. In almost all cases, the best results were obtained when the average phase advance was  $\pi$ .

The results showed that the nonlinear map norm can be reduced by up to 25-35%. This should be compared to the local compensation of a round beam where the wire reduced the map norm by nearly 2 orders of magnitude. Despite this small decrease in the map norm, the diffusion coefficients increased with the wire. As an example, horizontal diffusion coefficients with and without wire are shown in Figure 6 for case i). The wires increased the vertical diffusion as well in all cases.

## RESULTS AT INJECTION

At injection energy we followed a different approach. We used a lattice model that includes all known lattice nonlinearities, and as figure of merit we used the dynamic aperture (DA). The length of the wires were set to  $1m$ , the number of wires to four, and were placed them in long drifts available in the Tevatron, where the proton and anti-proton beams are well separated. When the parameters of all four wires had been optimized by short term tracking, the long term ( $10^6$  turns) DA was estimated. The results are contained in Table 1. The long-term DA increased by almost

$2\sigma$ . An independent check of the solution has been performed with another code [6], but neglecting all nonlinearities except the beam-beam. It was found that the DA increased vertically by roughly  $1.5\sigma$  for these wire parameters. Moreover, these results are not very sensitive to placement and current of the wires. For example a  $\pm 0.5mm$  offset in the wire transverse position did not alter the DA. The same is true for small static errors in the current values. Therefore, these results seem to show that in principle an improvement is feasible by current carrying wires, but a simple rule for their placement and current that can be used during operations is yet to be found.

DA [ $\sigma$ ]	Number of turns		
	$10^4$	$10^5$	$10^6$
<i>Beam-beam on, no wires</i>	6.0	4.0	<b>3.7</b>
<i>Beam-beam on, best case wires</i>	7.0	6.5	<b>5.5</b>

Table 1: At injection energy, using 4 wires and optimizing each of them individually by rastering we obtained an improvement of the DA by almost  $2\sigma$ .

## SUMMARY

Our purpose was to determine the feasibility of compensating the long-range interactions in the Tevatron with wires. At collision energy we found that local compensation of a single parasitic by a round wire works well when the strong beam is round but not when the beams are elliptical because the field profile from the strong beam cannot be matched by a round wire. Strategies for non-local compensation helped specify the ideal phase advances and transverse positions of the compensating wire. Particle diffusion however increased with the optimum wire settings for all cases studied. At injection energy we placed a wire in each of 4 warm straight sections and found currents and positions that increased the dynamic aperture by about  $2\sigma$ . However an operational strategy for optimizing wire parameters was not clear.

We conclude that there is no simple strategy for compensating the long-range interactions in the Tevatron using single wires at a few locations that will work at injection and collision. A successful strategy might involve multiple wires, perhaps with elliptical cross-sections, at several locations.

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