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PROGRESS WITH COLLISION OPTICS OF THE FERMILAB TEVATRON COLLIDER*

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Abstract

Recent advances in the measurement and modeling of the machine parameters and lattice functions at the Tevatron allowed modifications of the collision optics to be performed in order to increase the collider luminosity. As the result, beta functions in the two collision points were decreased from 35cm to 29cm which resulted in ∼10% increase of the peak luminosity. In this report we describe the results of optics measurements and corrections. We also discuss planned improvements, including the new betatron tune working point and correction of the beta function chromaticity.

INTRODUCTION

Detailed understanding of the machine optics proved to be essential for achievement of high luminosity at Fermilab Tevatron. First measurements of the collision optics using the Orbit Response Matrix method [1] (we also refer it as the differential orbit method) were performed in January, 2003 and revealed large discrepancy between the actual machine and the design [2]. Subsequent correction resulted in some 27% increase of the peak luminosity.

Later, a more advanced Linear Optics from Closed Orbit (LOCO) has been implemented on the basis of software developed at ANL [3, 4]. Recent commissioning of the new BPM system in May, 2005 allowed to improve accuracy of measurements. Since then, the method is used routinely for measurement of the collider optics. In this paper we present the results of improved measurements and modeling, and discuss the proposed development of the Tevatron collision optics.

OPTICS MODEL

In the Tevatron the beams of 980 GeV protons and antiprotons collide head-on in two low-beta Interaction Points occupied by CDF and D0 experiments. The beams move in the common vacuum chamber on helical orbits formed by electrostatic separators. Optics of the arcs consists of FODO cells (phase advance of 60 degree in both planes) with quadrupoles powered in series with the guiding field dipoles. Final focus quadrupoles in both IPs have separate power supplies. There are also several quadrupole, skew-quadrupole, and sextupole corrector circuits for control of betatron tunes, coupling, and chromaticity. The so-called feeddown sextupoles are used for differential control of tunes and coupling at the orbits of protons and antiprotons.

Computer model of the lattice uses power supply current settings from the control system and calibration curves for **each** quadrupole measured at the time of magnet production 25 years ago to determine the gradient as a zero approximation. On top of this approximation variable gradient and skew-gradient errors are applied to each quadrupole to fit the measured and computed differential orbits. Besides, the fit includes variable BPM gains and tilts, and dipole corrector calibrations and tilts [4].

MEASUREMENT RESULTS

Found Gradient Errors

The main factor limiting accuracy of the LOCO fit is the resolution of the beam position measurement. The new Tevatron BPM system has the resolution of about 10μm. Besides, the beams oscillate at low (∼10 Hz) frequency with the amplitude of about 50 μm. Averaging over 25 measurements has been applied to mitigate the effect of slow oscillations. The overall accuracy of the orbit measurement is then about 15μm. Figure 1 shows the r.m.s. difference of the measured orbit and the modeled orbit after the fit for each BPM. In this case, 30 horizontal and 30 vertical orbits were used and the average error was ∼14 μm which is close to the orbit measurement accuracy.

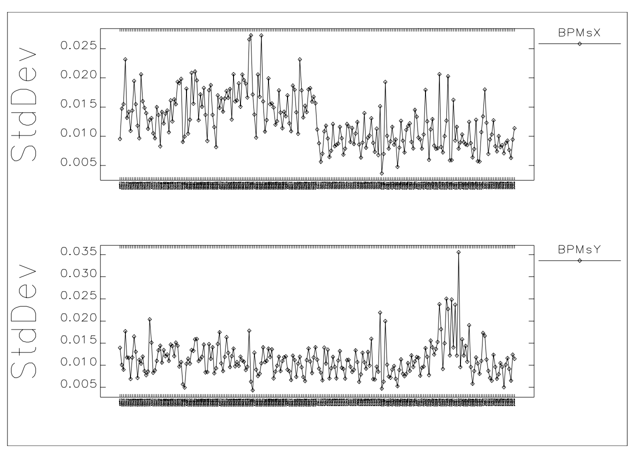

Figure 1: RMS difference between the measured and modeled orbit (mm) vs. BPM name. Top plot is horizontal orbit, bottom - vertical orbit.

The precision of the orbit fitting sets the accuracy of gra-

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dient error determination, which in our model is $\sim 10^{-3}$ for the arc quads and $\sim 10^{-4}$ for the final focus quads. The corresponding error in β-function is 5%. In Fig. 2 the found quadrupole and skew quadrupole errors are presented for all locations in the Tevatron. Two locations with

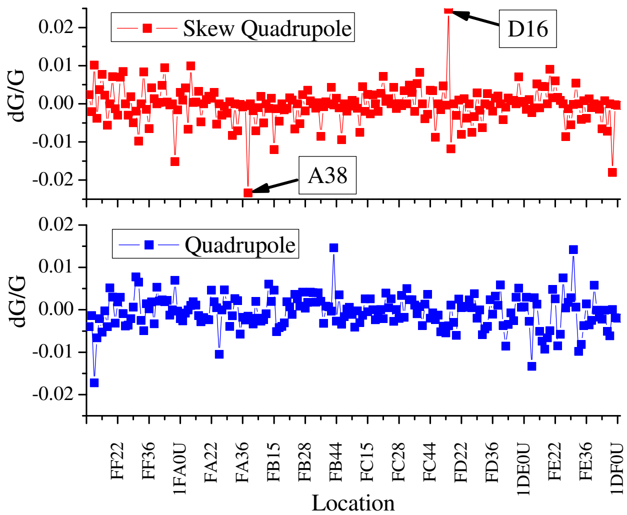

Figure 2: Measured relative quadrupole and skew-quadrupole errors.

large skew-quadrupole component, D16 and A38, have been identified as rolls of the corresponding quadrupoles. These rolls emerged at the magnet assembly and could not be identified from outside of the magnet.

Table 1 summarizes the gradient errors for the final focus quadrupoles. As one can see, the difference from the calibration curve obtained by magnetic measurements can be as high as 1%.

Table 1: Relative quadrupole errors in final focus

NAME	**Gradient Error** (10^{-3})
B0Q3	-11.18
B0Q2	-1.87
B0Q3D	-0.09
B0Q3F	-0.47
D0Q3	-9.49
D0Q2	-0.83
D0Q3D	0.24
D0Q3F	-1.84

Implementation of the New Optics

Based on the knowledge of the lattice details a new optics has been implemented in July, 2005 with the following goals:

- Eliminate beta-beating in the arcs.
- Correct the discrepancy in the values of β^* between two IPs.
- Decrease the value of β^* from 35cm to 28cm, with expected gain in luminosity of 11% (Fig. 3). Further decrease of the β^* is not desirable because of the growing second order chromaticity and little gain in luminosity due to hourglass effect.

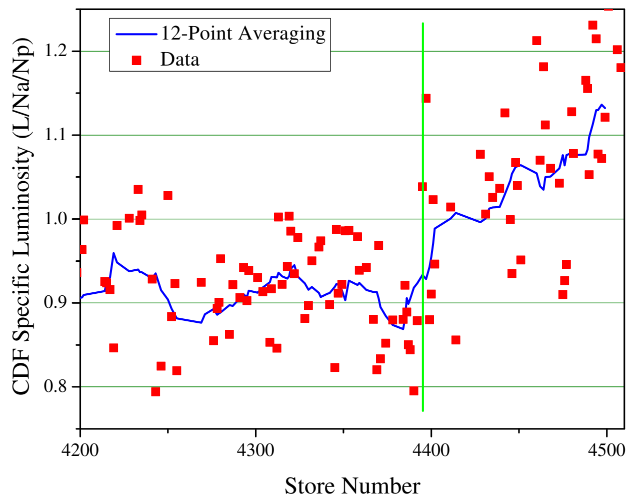

Figure 3: Specific initial luminosity ($L/N_a/N_p$) vs. store number. Green line marks the moment when the new optics was put into operation.

As the result, the following values of β-functions at the IPs were obtained:

Table 2: β^*-functions after correction

IP	β_x^* **(cm)**	β_y^* **(cm)**
CDF	30.3	29.1
D0	29.2	28.2

NEW WORKING POINTS

With the present beam intensities and emittances the beam-beam tune shift for antiprotons is 0.025. Tevatron now operates at the betatron tunes between the 7th and 5th order resonances, $Q_x \simeq Q_y = 20.58$, where the available tune space is 0.028. That sets the limit on future increase of the proton beam intensity. Hence, a major change of the betatron tune is considered as a possible way of the luminosity increase. Two potential candidates are proposed (Fig. 4), in the vicinity of the half integer resonance (20.52), and close to 2/3 resonance (20.672). Beam-beam simulations show that these two points have equal potential for increase of the proton beam intensity by 30% with no degradation of the antiproton beam life time and emittance growth. However, there are factors complicating implementation of the new working points. Both working points are located close to low order lattice resonances which have large natural width, and careful correction is needed to achieve the required enhancement of the tune space.

Width of the 2/3 resonance (measured 0.015) is dominated by distribution of sextupole errors and lattice sextupoles, and it is most important at injection energy. Studies have been done to pinpoint the locations of sextupole errors and possibly correct them [5].

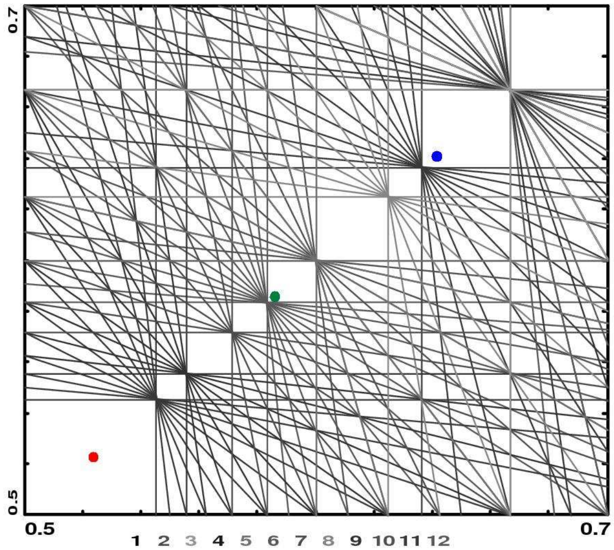

Figure 4: Betatron tune diagram with resonances up to 12th order shown. Green spot - present WP, red spot - 1/2, blue spot - 2/3

The half integer resonance is driven by quadrupole errors which cause distortions of β-function. Large beta-beating has been observed in the beam study (Fig. 5), and the measured resonance width was 0.02. Correction of this distortions is possible with special quadrupole corrector families available in the Tevatron with little modifications.

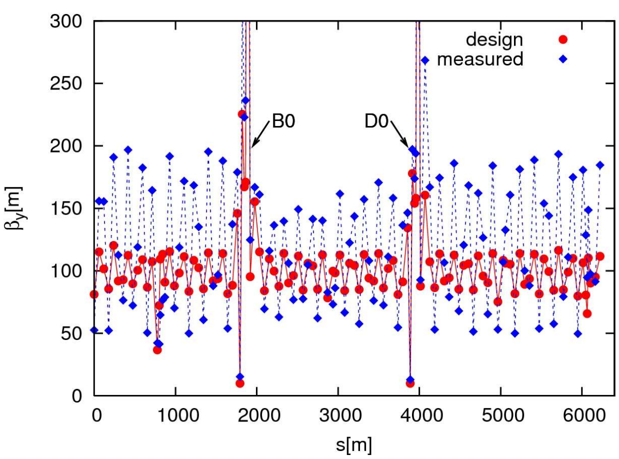

Figure 5: Vertical β-function (turn-by-turn measurement) close to half integer resonance. Qx=20.518, Qy=20.514

At the same, time there is one more contributing factor - chromatic focusing errors. The chromatic β-function has been measured using the differential orbit method at two revolution frequencies (Fig. 6). The maximum value of 500 corresponds to the β-function change of 20% on the size of the energy aperture. This also results in undesirable coupling between the longitudinal and transverse degrees of freedom at the IPs making the beam-beam effects more detrimental to the luminosity. In order to correct the chromatic focusing perturbations a rearrangement of the existing sextupoles into the so-called second order chromaticity correction families has been proposed. Implementation of this rearrangement will allow to decrease the chromatic β-function in the arcs by roughly a factor of three and almost completely eliminate it in the IPs.

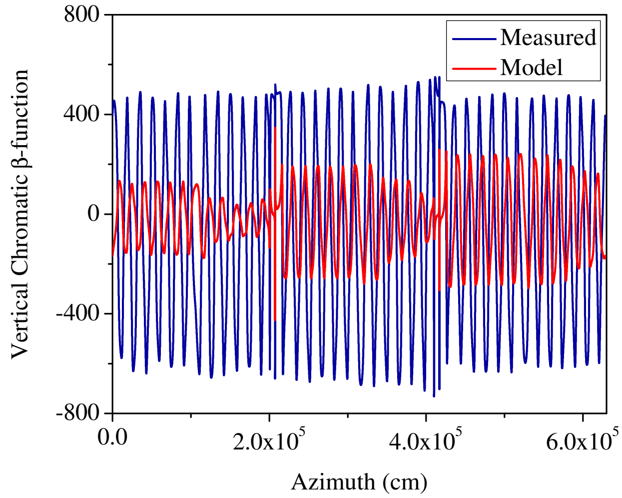

Figure 6: Vertical chromatic β-function ($\frac{\Delta\beta/\beta}{\Delta p/p}$). Blue line - measured, red line - proposed correction.

CONCLUSION

The Orbit Response Matrix method with the new Tevatron BPM system allows to find lattice gradient errors of $\sim 10^{-3}$. This tool played the major role in successful implementation of the new collision optics which increased the peak luminosity by 10%. The plans of further luminosity growth require operation with higher beam intensities, which demands a change of the betatron tune working point and correction of the chromatic perturbations in the optics. The new sextupole families have been designed to correct the second order chromaticity. Their commissioning is planned later in 2006.

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