Time-Varying Sextupole Corrections During the Tevatron Ramp

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Abstract

We have studied the time behavior of the sextupole component (b_2) of Tevatron superconducting dipoles under ramping conditions. Large time-dependent sextupole corrections are necessary to maintain constant chromaticities. in the Tevatron. We discuss the implementation and results of these corrections in terms of emittance growth and intensity loss during the Tevatron ramp.

Introduction

During early operation of the Tevatron as a collider it was discovered that the dipole magnets exhibited time-dependent behavior[1,2]. For injection of p's and $\bar{p}$'s, the Tevatron energy is set to 150 GeV for up to a few hours (the 'injection porch') while the injection processes are tuned up. During this period the horizontal and vertical chromaticities were seen to change systematically by 10's of units. These changes were traced to time-dependent changes in b_2 in the dipoles. Chromaticity changes are compensated with sextupole circuits, and the corrections for this effect have been measured and installed in the Tevatron control programs.

An additional effect observed later is the behavior of b_2 of the dipoles at the start of the ramp to continuously monitored with a spectrum analyzer connected to Schottky plates, and at the start of the ramp the tune lines would disappear and reappear several seconds later. The normalized transverse emittances also grew by up to 10π mm-mr during the ramp, and there was some loss of bunched beam. As a result of these observations, a series of laboratory measurements on a single Tevatron-style dipole magnet. The results of these experiments indicate that the Tevatron dipoles experience a rapid change in b_2 (1 unit, in units of 10^{-4}in^{-2}, or 30 units of chromaticity in the Tevatron) at the onset of the ramp. We will also show how we have compensated this effect operationally.

Some simple arguments will demonstrate the importance of controlling ξ, especially at 150 GeV. The Tevatron working point has been chosen to be $\nu_x = 19.415$, $\nu_y = 19.410$. The only nearby resonances under order 12 are the $2/5^{th}$ (19.4) and the $3/7^{th}$ (19.429). Thus, the working area is roughly 0.015 wide. At 150 GeV, σ_p/p for the 3.1 ev-sec Tevatron bunches is $0.5\text{x}10^{-3}$. Assuming a 4σ envelope, the tune spread $\Delta\nu = \xi(\Delta p/p)$, is $\Delta\nu = 0.01$ for $\xi = 5$, so the working area is already filled and the tunes will overlap resonances. Additional tune spreads, such as due to the beam-beam interaction, must be accommodated within this space. In the Tevatron ξ must be greater than 0 to avoid instabilities. Given these constraints and our inability to control the Tevatron perfectly, we would like to keep $2 < \xi < 4$.

Laboratory Measurements

The laboratory measurements utilized a vertical Dewar and a 0.81 m. long Tevatron-style coil[3]. This magnet differs from those in the accelerator in its length and in its absence of the iron yoke. The coil can be ramped with the Tevatron ramp waveform but with a magnitude 1.2 times greater to compensate for the missing yoke. The transfer function for the coil is 5.33 amp/GeV. The magnet was immersed in a Dewar with liquid He at 4.2° K. The Tevatron magnets are cooled to 4.7° K. Although the width of the hysteresis curve depends upon temperature, we have no evidence that the time dependence does. Magnetic measurements were made with a 0.47 m. long Morgan coil rotating at 6 Hz and read out every other turn. The Morgan coil was centered in the magnet to ensure that end fields were not measured. We used only the dipole and sextupole windings of the Morgan coil.

Before each experiment the coil was powered to 4000 A. and quenched. After it was re-cooled it was ramped from 90 GeV to 900 GeV 6 times and finally set at the 150 GeV level (800 A.). Apart from the quench, this procedure is identical to what is done to Tevatron magnets before injection. The experiments consisted of holding the current at the 150 GeV level for different lengths of time and then ramping to 900 GeV and back down. During the injection porch magnetic data were recorded every few seconds, and during the ramp, at the maximum rate of 3 Hz.

In Fig. 1 we plot the hysteresis curve, $b_2(E)$, for a Tevatron cycle with no injection porch. The arrows indicate increasing time. Knowledge of this curve is essential to Tevatron operation, since the sextupole currents are calculated using the contribution to b_2 from the dipoles. If a 900 sec. porch is included, the curve becomes the one in Fig. 2. During the 900 seconds, b_2 has drifted positive by about 1 unit. This effect has already been measured and corrected. What was not known was how b_2 behaves once the ramp starts. From the plot we can see that in the first 40 amps (2 seconds) of the ramp b_2 changes by about 1 unit and joins the hysteresis curve. In the Tevatron 1 unit of b_2 corresponds to almost 30 units of chromaticity. As shown in the Introduction, this is sufficient tune spread to excite resonances.

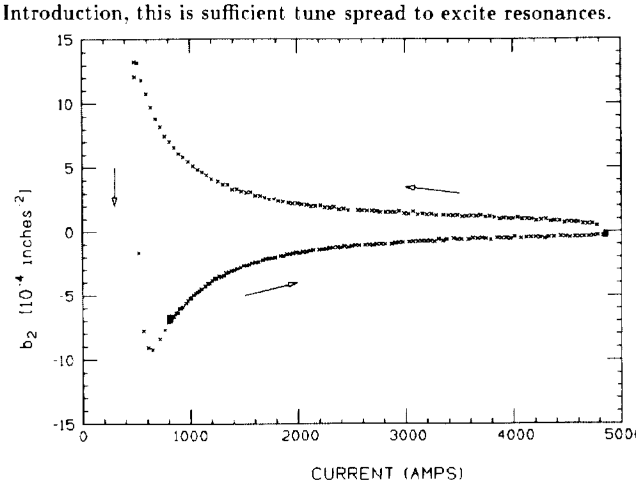

Figure 1: Hysteresis for a Tevatron-style magnet. The arrows indicate increasing time.

In the 1987 collider run this rapid change in b_2 was not known. All that was known was that at the start of the ramp the tune lines disappeared and re-appeared several seconds later. It was assumed that they re-appeared when b_2 joined the hysteresis curve. The correction during the several seconds was simply to hold b_2 constant at the value to which it had drifted during the injection porch. After this value of b_2 became equal to that of the hysteresis curve, the hysteresis curve was used. Thus, for several seconds the Tevatron chromaticities were

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over 30 units away from our goal of $2 < \xi < 4$.

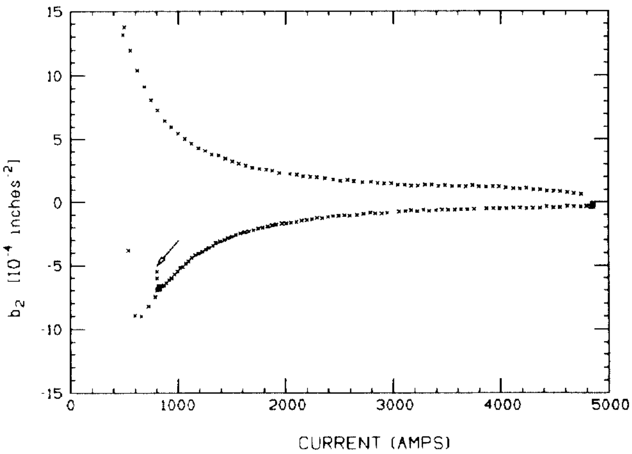

Figure 2: Hysteresis curve with a 900 sec. injection porch. The arrow indicates the level to which b_2 has risen during the 900 sec.

We further investigated this curve by varying the length of the injection porch from 900 to 21000 seconds. This covers the range of the porches experienced in Tevatron collider operations. In Fig. 3 we plot the data in the region of the start of the ramp. We see that the connection between the final value of b_2 on the injection porch and the hysteresis curve $b_2(E)$ depends upon the length of the porch. However, we have not been able to find a functional form which depends only upon the length of the porch.

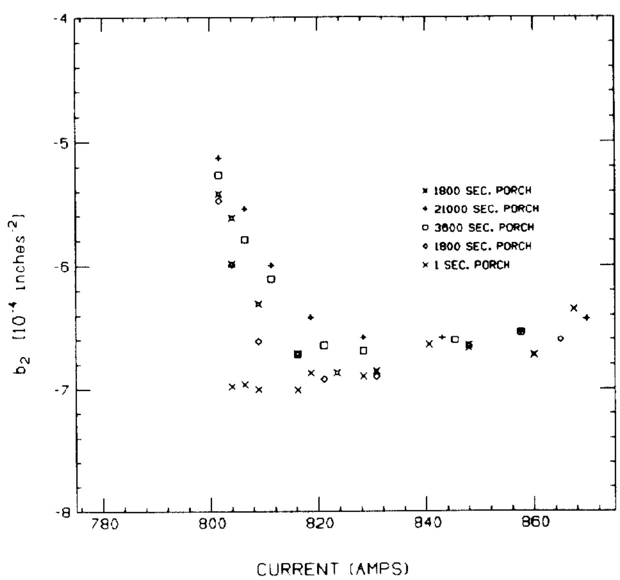

Figure 3: Hysteresis curve for various injection porches at start of ramp.

For the 1988-1989 collider run these data were installed in the Tevatron Colliding Beam Sequencer (CBS)[4] program for sextupole control. The CBS controls all aspects of Tevatron Collider operations. For each injection porch the data points were read off of Fig. 3 and the difference between that curve and the hysteresis curve calculated as a function of energy. Immediately before the ramp the length of the injection porch is calculated, and the ramp table to be used is formed by linearly interpolating between curves in length of porch and energy. This value of b_2 is then added to the value of the hysteresis curve at that energy. From the value of b_2 and the requested ξ_x and ξ_y the sextupole currents are calculated and then loaded into the hardware ramp generators.

Tevatron Results

One test of this algorithm was to measure ξ and see how well it is kept in the range of 2-4. To do this we took the Tevatron through two complete cycles (6 ramps, 1 1/2 hour injection porch, ramp to flattop) with different RF frequencies, or momenta. The difference in RF frequencies was chosen to give a 1 mm. change in orbit radius. The tunes were recorded by taping the spectrum analyzer trace and later measuring the locations of the peaks. ξ_x and ξ_y for the early part of the ramp are shown in Fig. 4. During this period the changing b_2 in the dipoles is causing ξ to change by 30 units, but the algorithm we developed has succeeded in keeping ξ constant to 2 units. There is a brief period in which ξ_x became negative. Examination of the spectrum analyzer trace showed that indeed ξ_x was negative or very near 0. The negative chromaticities were eliminated by increasing the requested ξ_x.

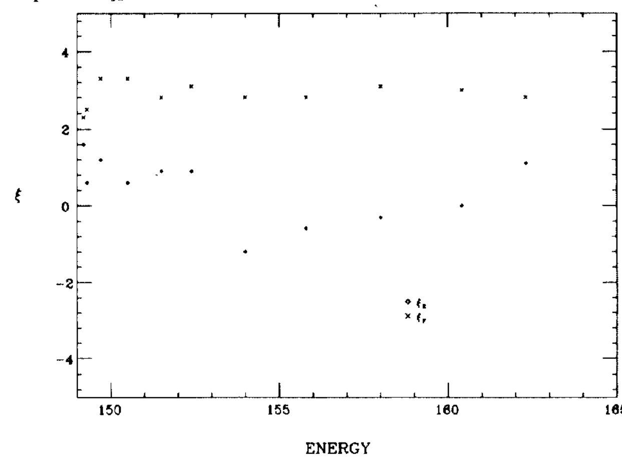

Figure 4: Measured Chromaticities of the Tevatron at the start of the ramp.

Another measure of the quality of the ramp is the emittance growth. During the 1987 run the proton transverse emittances increased by 1 to 4 π mm-mr in each plane, and the $\bar{p}$ emittances by 10-20π mm-mr in the ramp. The larger $\bar{p}$ emittance growth may have occurred because the average p intensity during the run was 5 times the $\bar{p}$ intensity. The beam-beam tuneshift combined with the tune spread due to chromaticity may have caused the $\bar{p}$ tunes to overlap resonances. Unfortunately, in the 1987 run the transverse emittances were measured only at 150 GeV and at flattop (and low-β), so we don't know when in the ramp the emittance increases occurred. In the 1988-1989 run we had the capability of measuring the transverse emittances at one point on the ramp. In a series of stores in Dec. 1988 this point was chosen to be 400 GeV. The results for the emittances at 150 GeV and 400 GeV for some of these runs are listed in Table 1, along with the intensities of each beam. The average emittance growths are less than 0.5π mm-mr, and are consistent with 0 emittance growth. We did not measure the intensities at 400 GeV. However, the overall transmission of p's and $\bar{p}$'s to 900 GeV was over 96%.

Conclusions

Although the sextupole field components in the Tevatron dipoles change by up to 2 units (60 units of chromaticity) during the first 15 GeV of the Tevatron ramp, it is possible to compensate this effect. Tevatron data show that the beam intensities and beam qualities are unchanged during this period.

References

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TABLE 1: Emittances During Ramp in units of π mm-mr.

STORE	ENERGY	ϵ_h^p	ϵ_v^p	$\epsilon_h^{\bar{p}}$	$\epsilon_v^{\bar{p}}$
1880	150	16.0	17.5	11.5	12.4
1880	400	16.3	19.2	10.5	14.0
1884	150	18.4	20.4	8.6	10.0
1884	400	18.6	21.0	8.6	9.9
1886	150	18.0	20.1	8.7	10.3
1886	400	17.9	20.5	8.8	10.3
1893	150	24.8	28.1	9.2	10.3
1893	400	24.4	25.7	8.1	9.9
1898	150	27.1	26.6	9.7	10.5
1898	400	24.9	28.0	9.3	10.2