TIME DEPENDENT CHROMATICITY CHANGES IN THE TEVATRON

D. A. Finley, D. A. Edwards, R. W. Hanft,
R. Johnson, A. D. Mc Inturff, and J. Strait
Fermilab[*], Batavia, Il. 60510

The Tevatron Collider energy is held constant at 150 GeV for some time while proton and antiproton bunches are injected prior to acceleration and storage. Under these conditions the machine chromaticity has been observed to change by as much as 70 units over the course of several hours. The data are consistent with a decay of the sextupole component of the 774 superconducting dipoles in the ring. Measurements of individual magnets in the Magnet Test Facility show similar behavior. An operating procedure has been devised to compensate for the chromaticity changes which gives a satisfactory beam lifetime.

Introduction

The chromaticity of the Tevatron is a particularly important parameter for collider operation. First, since the machine operates above transition, the chromaticity must be positive to avoid the head tail instability. Second, since the rf buckets are almost completely filled for maximum bunch intensity, the chromaticity must be small enough that the large momentum spread does not create a tune spread which is too large.

The lifetime of a weak antiproton beam in the presence of a strong proton beam is very sensitive to details of the working point. Ordinarily innocuous resonances can be devastating in the presence of the beam-beam interaction. In the Tevatron we have chosen to work between the 5th and 7th integer tune lines, where a total tune spread of about ±.01 is available, free of resonances up to 16th order. Tune spreads due to the beam-beam interaction (which increases the antiproton tunes), the space charge tune shift (which only slightly decreases the proton tunes at 150 GeV), and the spread due to the chromaticity must all be accommodated within this ±.01.

An rf bunch of 3.1 eV-s occupies ±1E-3 $\Delta p/p$ at the 150 GeV injection energy. The tune spread, $d\nu = \xi \ \Delta p/p$, completely fills the working area for ξ=10. Since the area is already almost filled by the antiprotons due to the beam-beam tune shift, the conclusion is that the chromaticity must be no larger than 1 or 2 units to avoid beam degradation. It can be noted that the problem also exists at 900 GeV but the momentum spread is a factor of 3 smaller and the constraints on the acceptable chromaticity are correspondingly relaxed.

Since the proton bunch intensities are already approaching their design values of 6E10, all of the contributions to the tune spread are present at their ultimate design values even though it is very early in the history of the collider. And it has been found that the chromaticity must be held to less than a few units to avoid transverse emittance growth and eventual beam loss.

First Observations

During the initial coasting beam tests with the Tevatron, large changes in the beam behavior over the course of several hours were shown to be due to changes in chromaticity. Further, there were large variations in initial tunes and chromaticities which depended on the details of the recent history of the machine (e.g., whether the ramp had been turned off completely or how many ramps to flat top had been performed before setting at 150 GeV).

Ramp History

Figùres 1a and 1b show two extremes in the history of the machine. In figure 1a, the machine had been ramping to 900 Gev every 2 minutes for the 2.5 hours prior to setting at 150 GeV. The tunes as a function of time and momentum offset are shown. The settings of the correction elements which determine the tunes, chromaticities, skew coupling, and closed orbit were much the same as used for fixed target operation of the machine. The chromaticity as shown by the slope of the lines on the plot is easily seen to change in the two planes, quickly at first, then more slowly as time progresses.

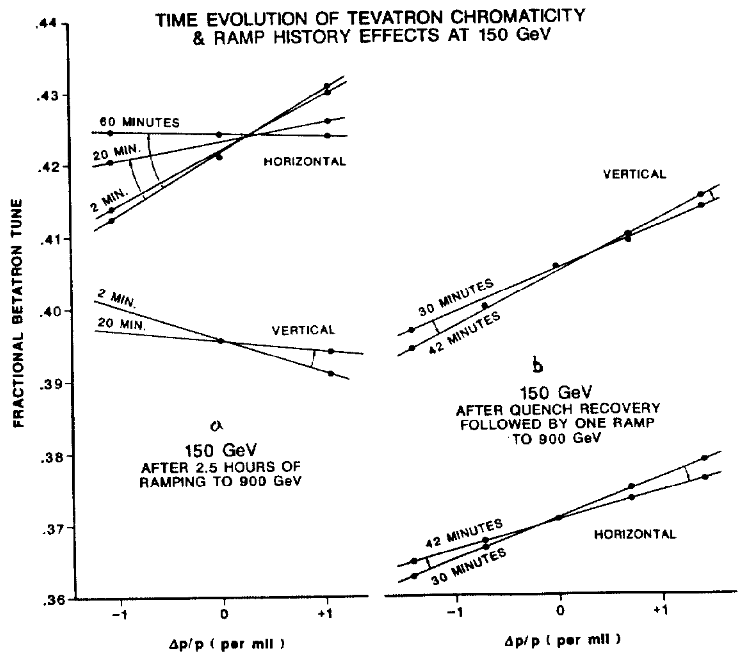

Figure 1. Temporal changes of tune vs $\Delta p/p$ while the Tevatron energy is fixed at 150 GeV. Figure 1a shows measurements following 2.5 hours of ramping to 900 GeV. Figure 1b shows measurements taken after a single ramp to 900 GeV.

Figure 1b shows similar measurements where the history of the machine is much different. In this case, there had been a quench in a magnet, necessitating turning off all power supplies. After recovery the magnets were ramped to 900 GeV, down to 90 GeV then back to 150 GeV where the measurements on figure 1b started. The 90 GeV reset level is a feature of all ramps. In case 1b, the initial tunes are quite different from case 1a as are the initial chromaticities. The causes of these changes is not understood in detail. The consequence of the measurements was to institute a policy of starting each 150 GeV store with a series of 6 ramps.

The chromaticity of the machine, ignoring the settings of the correction sextupoles, is given by

$$\xi_x = -22.5 + \langle \eta \beta_x b_2 \rangle \text{ and}$$
$$\xi_y = -22.5 - \langle \eta \beta_y b_2 \rangle,$$

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where -22.5 is the natural chromaticity of the machine, η the local dispersion function, β the betatron amplitude function, and b_2 the coefficient of the sextupole component of the magnets in the ring. The average is usually made over the 774 dipoles in the ring, where Magnet Test Facility (MTF) data were used for the initial operation of the Tevatron.

Measurements

Measurements of the change in chromaticity reported below were actually made by adjusting the correction sextupole circuits to obtain $\xi=0$. The uncorrected chromaticity was inferred by the currents in the sextupole circuits. This method has advantages over measuring tunes at different momentum offsets. The first is that the needed corrections are determined by the measurement. The second is that it is faster; one quickly sees that you are on the wrong side of zero because the beam becomes unstable and the resulting coherent transverse oscillations are easily seen on a spectrum analyzer connected to a position monitor. The number of synchrotron tune side bands is also a measure of the chromaticity. Usually one can quickly adjust the correction sextupole settings to eliminate the synchrotron sidebands, which implies a chromaticity very near zero.

In all of the data, the horizontal and vertical chromaticities were observed to change in equal and opposite directions. Since this behavior is consistent with a time varying sextupole moment of the machine, we have interpreted the data in terms of the single parameter $\langle b_2 \rangle$. The implication is that the sextupole moment of the 774 superconducting dipoles in the ring changes with time and the beam measurements are only sensitive to the average over all the dipoles.

Data taken under controlled conditions

Figure 2 shows the results of measurements over many different stores. The abscissa is elapsed time, starting from when the machine was set to the 150 GeV injection level. In most cases there were 6 ramps to 900 GeV preceding this event; prior to that, the machine was usually in a 900 GeV store. The ordinate of figure 2 is the $\langle b_2 \rangle$ inferred from setting the chromaticity prior to injecting protons and antiprotons for collider operation. Indicated at time zero is the value of $\langle b_2 \rangle$ found empirically during fixed target operation. In this case the beam was injected about 2 seconds after the ramp reset and was immediately accelerated.

Errors

The measurements using the elimination of the synchrotron sidebands have a systematic error associated with the variation of the momentum spread from day to day. (i.e., f_s = 80 Hz,

$\nu_s = f_s/f_{rev} = 80/47747 = .0017$; if no synchrotron tune line is seen and $\Delta p/p = \pm 1E-3$,

$\xi < \nu_s/(\Delta p/p) = 1.7$). In some cases the momentum spread can be smaller than 1E-3 due to operational problems and we have assigned a systematic error of ±3 units of ξ to the data on figure 2. Judging by the excellence of the fit to the exponential decay, this error is overestimated.

Temperature variations

One of the first things suspected as a cause for the change of $\langle b_2 \rangle$ with time was temperature variations. Certainly the D.C. ramp at 150 GeV reduces the refrigerator load and one could imagine that the temperature would change in the superconducting magnets which could affect their field quality and in particular, the persistent current sextupole. In fact, the temperature is well monitored and does not change more than 0.1 degree Kelvin over the period of the measurements. To account for a +2 unit increase in $\langle b_2 \rangle$ from a change in persistent currents one needs a temperature <u>increase</u> of more than 3 degrees.

Eddy current effects

One hypothesis which still survives to explain the time variation of $\langle b_2 \rangle$ is due to Alvin Tollestrup (in a CDF note dated Dec. 10, 1986). He supposes that the twisted superconducting filaments imbedded in the copper strands form tiny loops which are closed by the copper itself. The copper is not superconducting but it is cold and has a relatively low resistance. Thus L/R time constants of minutes or hours can be imagined. As yet, there is no quantitative explanation based on this hypothesis and certainly no easy way to explain at least 2 separate time constants seen in the data. As well, the chromaticity is observed to be constant for long times during 900 GeV stores. This seems contrary to the most simple eddy current model.

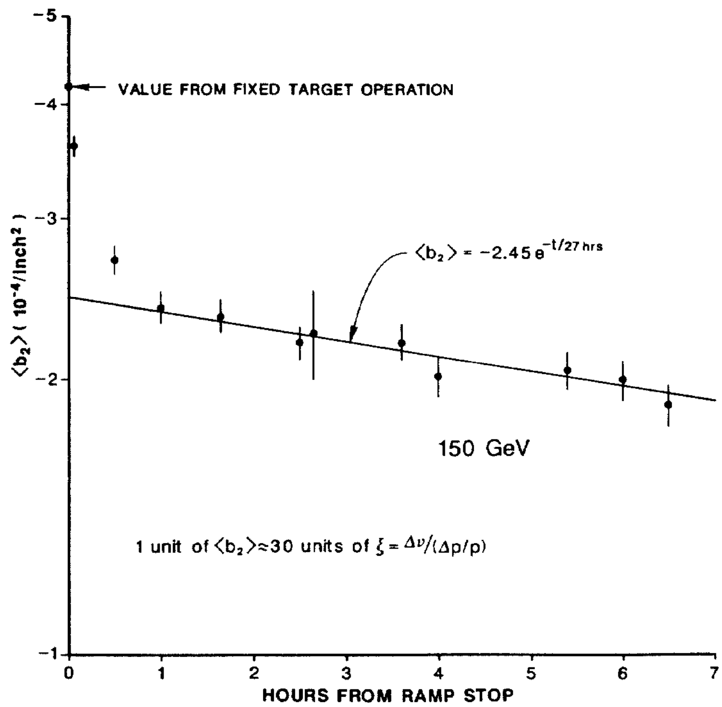

Figure 2. Temporal variation of $\langle b_2 \rangle$ for the Tevatron with well defined initial conditions. For most of the data, the Tevatron was ramped 6 times to 900 GeV before being set at the 150 GeV injection level.

Operational Cures

During these early days of commissioning the Tevatron Collider preparations for antiproton transfers have usually taken more than an hour. As seen in figure 2, most of the rapid variation in chromaticity has ended by then. It has been a simple matter to read the curve and set the $\langle b_2 \rangle$ to give acceptable chromaticities. In the near future this task will be given to the program which runs the accelerator complex during Collider operation and, hopefully, it will be done automatically.

As the antiproton transfers become more routine and faster, one hopes that the normal time at 150 GeV will become much less than one hour. In this case the temporal variation of $\langle b_2 \rangle$ will have to be mapped out much more carefully and the corrections applied more often.

The biggest outstanding operational problem is now the transition from the 150 GeV storage situation to the ramp to 900 GeV. There is mounting evidence that there are chromaticity variations at the beginning of the ramp which lead to transverse emittance growth of both the proton and antiproton beams. More study is needed.

Magnet Test Facility Data

Figure 3 shows MTF measurements taken on a Tevatron style coil of b_2 versus time. There is no iron around the coil and the data were taken for about 15 minutes after the ramp stopped, but the general characteristics are as expected from the Tevatron beam measurements. Namely, there is a large change in the first 100 seconds and a slower rate of change in the next 15 minutes. MTF data for periods longer than 15 minutes do not exist.

There are data from a few other coils which show similar behavior. These data were taken using a rotating Morgan coil. An MTF program of measuring the long time behavior of superconducting magnets is just starting.

Conclusions

An unexpected characteristic of the Tevatron has been investigated. Using beam measurements, the temporal variation of the sextupole component of the ensemble of magnets has been mapped out. Measurements of the behavior of a small sample of test coils verify that superconducting magnets can have significant field quality variation with time.

Operational problems associated with the demanding requirements of antiproton-proton collider operation have been (at least) temporarily solved. Future improvements will only be possible through further study and understanding.

Needed Improvements for Luminosity Upgrades

Schemes for improving the luminosity often involve storing antiprotons in the Tevatron for long periods while protons are replaced regularly. This means decelerating and reaccelerating the pbars. To do this without beam loss will require a very thorough knowledge of the sextupole behavior of the superconducting magnets in the ring. The temporal variations of the sextupole components add an interesting new dimension to an already fascinating problem.

Implications for the SSC

While we have primarily discussed the chromaticity changes of the Tevatron as a function of time, one must also be concerned with other sextupole effects. And, since the only measurements we have made on the Tevatron are of the ensemble average, there is no knowledge of the temporal variations of individual dipoles.

The SSC dynamic aperture is expected to be determined by the randomly distributed sextupole component of its superconducting dipoles. Care must be taken to insure that the SSC magnets have sextupole components that do not imply a time variation of the random sextupole distribution.

Acknowledgments

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References

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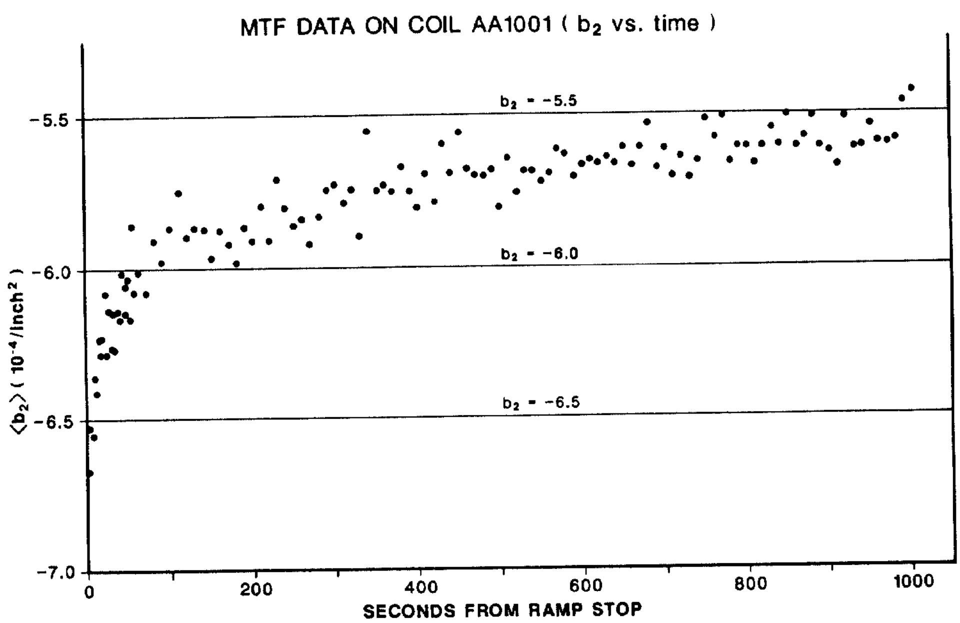

Figure 3. Magnet test Facility data showing b_2 vs time for a test coil similar to the coils of Tevatron magnets. Two different time constants are seen in the first 1000 seconds.