LUMINOSITY LIFETIME IN THE TEVATRON

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Abstract

Since the inauguration of colliding proton-antiproton operations in 1987, the Tevatron has exhibited luminosity lifetimes shorter than expected. During a typical colliding beam storage period, called a store, luminosity is calculated periodically by measuring the charge and emittances of each bunch. The growth of the transverse bunch emittances is the dominant cause of luminosity deterioration. Throughout this period, the position spectrum of the bunches exhibited betatron signals larger than expected from Schottky noise. A model assuming externally driven betatron oscillations explains both the betatron signals and the emittance growth.

A program is underway to improve the Tevatron luminosity lifetime. The abort kickers have been identified as sources of emittance growth, and some quadrupole power supplies are further candidates. Because the horizontal dispersion through the RF cavities is nonzero, RF phase noise has been investigated. Noise in the main dipole regulation circuit has also been studied.

Motivation

The two dominant transverse emittance growth mechanisms predicted for Tevatron colliding beam conditions are intrabeam scattering and the beam-beam interaction [4]. In 1987 the transverse and longitudinal emittances were greater than the design values, and the antiproton intensity was typically a factor of five to ten times smaller than designed. Therefore, the beam-beam interaction and intrabeam scattering effects were less severe than planned, and the observed luminosity lifetime (8 hours) should have easily exceeded the design estimate (20 hours). Also, the invariant 95% emittance growth rates were between 1 and 8 π mm-mrad/hr [5]. The larger effect, intrabeam scattering, is predicted to induce an emittance growth rate of 0.2 ± 0.1 π mm-mrad/hr [6].

During a series of accelerator experiments, from December 1987 to March 1988, the proton transverse emittance growth rate in the absence of antiprotons and under otherwise standard Tevatron colliding beam conditions was measured to be 5.42 ± 0.08 π mm-mrad/hr. A calculation [7] of the dependence of integrated luminosity on transverse emittance growth rate was done. By reducing the growth rate to near the above intrabeam scattering prediction, it is shown that the integrated luminosity of a 10 hour store might be increased by as much as a factor of two.

Emittance Growth Models

Dipole Kicks

Driven betatron oscillations were observed during periods of transverse emittance growth [8]. This conclusion is based on the power in betatron sidebands of the beam spectrum measured with resonant, parallel plate detectors designed to record Schottky signals. Power levels almost two orders of magnitude above the expected Schottky magnitude were measured, and interpreted as evidence for externally driven betatron oscillations. Assuming each bunch oscillated independently, the measured oscillation amplitude was 0.35 μm [8], close to the wavelength of blue light.

Assume a model in which driven beam oscillations are damped by tune spread, producing transverse emittance growth and a constant oscillation amplitude. If the source of this motion is a random dipole kick acting identically on all the particles of the beam (with the square of the rms deflection angle written as $|N(\omega)|^2 \Delta\omega$), then the rms emittance growth rate in units of m-rad/sec is [9]

$$\dot{\epsilon} = \pi f_o \beta \Sigma(|N(\nu)|^2) \Delta\nu \quad . \qquad (1)$$

The beam revolution frequency is f_o (47.7 kHz), ν is the betatron tune (roughly 0.4 in both planes), and β is the value of the focussing function at the position of the source of the kick. The noise density at all betatron sidebands $\Sigma(|N(\nu)|^2)$ contributes to the growth rate. Note that the transverse emittance growth rate depends linearly on the beta function at the kick location and quadratically on the kick strength, predicting that the beam size grows as the square root of the number of turns. This is the expected behavior of a harmonic oscillator weakly coupled to a noise source. The invariant 95% emittance growth rate is 6 p/m times the right hand side of equation (1), where p/m is the beam momentum divided by the proton rest mass.

The dependence of the driven betatron oscillation amplitude $\langle x\rangle$ on the kick power spectrum depends in detail on the distribution of the individual proton tunes as a function of time. Assuming an exponential decay of the oscillation envelope yields the relationship [9]

$$\frac{\langle x\rangle^2}{\beta} = \frac{1}{8\pi\alpha} \beta \Sigma(|N(\nu)|^2) \Delta\nu \quad , \qquad (2)$$

where α is the decay rate in units of inverse revolutions. Since this rate depends on magnetic lattice nonlinearities (which is a function of tune and closed orbit trajectory) and chromaticity, the rms betatron oscillation amplitude may vary with Tevatron adjustments even though the dipole kick amplitude remains constant.

Quadrupole Variations

Assume that the strength of a quadrupole in the lattice has a component which is time dependent. There are two basic components of the effect on the beam emittance. First, if the closed orbit through the magnet is not at the magnetic center, a field strength fluctuation will produce a dipole kick, with the repercussions discussed in the previous section.

The second effect is emittance growth due to phase space ellipse modulation. If β is the beta function at the quadrupole and ΔK (the rms modulation of the inverse of the quadrupole focal length) has a white noise spectrum, then the rms rate is [10]

$$\dot{\epsilon} = \frac{f_o}{2} (\beta \Delta K)^2 \epsilon \quad . \qquad (3)$$

The instantaneous growth rate depends on the emittance and the square of both the beta function and the strength modulation. In the case where the power spectrum of ΔK is not flat, the frequencies corresponding to twice the betatron tune influence the emittance growth rate [11].

Tevatron Conditions

The standard colliding beam lattice is called the low-β lattice [4]; this lattice requires a number of additional quadrupoles at the B0 interaction region in the Tevatron. The purpose of the low-β configuration is to lower the β-function at the collision point.

The transition between the injection (fixed target) and low-β lattices is called a squeeze, and consists of a sequence of 25 steps. Some accelerator studies are done at step 5 of this sequence, since the interaction region quadrupoles at this point are partially powered and the β-functions is already very different from its injection values.

During most studies reported below, 6 bunches with a typical intensity of 4×10^{10} protons per bunch were circulated at an energy of 900 GeV. The available instrumentation allowed periodic measurements of bunch intensity, length, momentum spread, horizontal emittance, and the DC beam intensity. Reliable vertical emittance measurements were not available.

Experimental Results

Abort Kickers

The antiproton abort kicker, which deflects the beams horizontally in the event of an abort trigger, was the dominant source of horizontal emittance growth. The proton abort kicker, which deflects the beams vertically, was observed to be the dominant source of vertical betatron oscillations, and hence the dominant source of vertical emittance growth.

Figure 1 shows the result of turning the antiproton abort kicker off and back on at 900 GeV in the injection lattice. The horizontal emittance growth rate decreased from 3.36 ± 0.08 to 0.71 ± 0.03 π mm-mrad/hr when the kicker was turned off. All quoted growth rates were calculated by fitting the emittance vs. time data with a linear least squares fit. At the same time, the betatron sideband amplitude of the horizontal proton spectrum decreased by approximately a factor of two. Comparing equations (1) and (2), a factor of two decrease in oscillation amplitude should correspond to a factor of four decrease in the emittance growth rate, which is indeed the case.

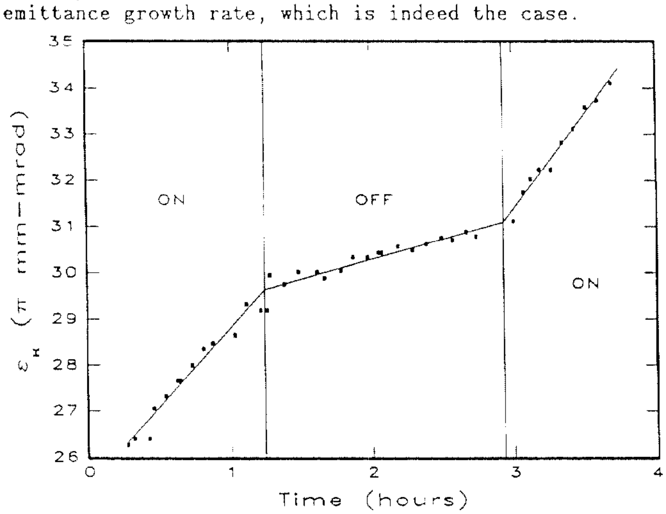

Figure 1: Horizontal emittance as a function of time while the antiproton abort kicker is on and off.

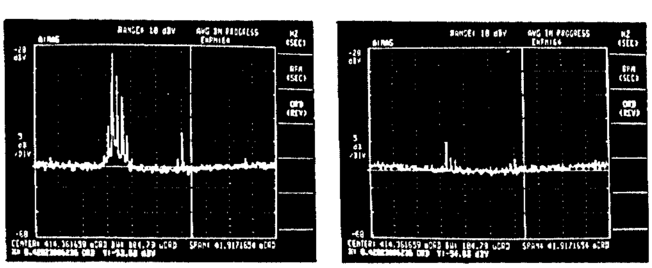

Figure 2: Proton spectrum when the proton abort kicker is on (left) and off (right). The vertical scale is 5 dbV/div and the horizontal tune scale is 0.0042/div. A vertical position detector was connected to the spectrum analyzer, and the horizontal betatron spectrum (near cursor) is present due to coupling.

Figure 2 contains the proton spectra when the proton abort kicker is on and off. Note that the amplitude of the vertical betatron spectrum dropped by an order of magnitude when the kicker was turned off. No vertical emittance data is available, but reducing the noise content of the proton abort kicker field is clearly necessary.

The proton and antiproton abort kickers used the same type of circuit, in which the current charging the storage capacitor flowed through the kicker magnet. A series of simple and inexpensive modifications have reduced the total noise power at the betatron sidebands, and hence the emittance growth rate, by 10^5. Therefore, the expected horizontal emittance growth rate due to the antiproton abort kicker for the next collider run is approximately 3×10^{-5} π mm-mrad/hr. The vertical growth rate due to the proton abort kicker should also be negligible.

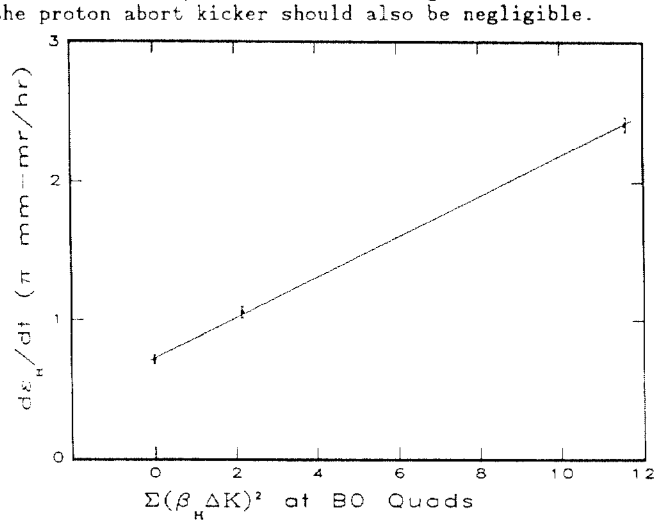

Figure 3: Measured horizontal emittance growth rates as a function of the driving term for phase space mismatch dilution due to B0 quadrupole strength fluctuations (right hand side of equation 3).

B0 Quadrupoles

With the abort kickers off, the horizontal emittance growth rate in the injection lattice was 0.71 ± 0.03, whereas in the low-β lattice it was 2.42 ± 0.05 π mm-mrad/hr. In an attempt to understand this difference, the low-β squeeze sequence was suspended at step 5. The horizontal emittance growth rate at step 5 was 1.06 ± 0.04 π mm-mrad/hr.

During a squeeze the only accelerator components which change appreciably are at the B0 interaction region. In addition, the dominant change in the β-functions occur at B0. Therefore, it is logical to suspect that the next most important source of emittance growth is at B0. The two candidate sources, even after calculations of the shielding effect of the stainless steel beam pipe [8], are the correction dipoles, which will be studied in the future, and the low-β quadrupoles with unfiltered power supplies, of which there are four on either side of the B0 interaction point.

These quadrupoles are off in the injection lattice. They are powered at the start of the squeeze, and observations show that their voltage spectrum (composed of 720 Hz harmonics) is independent of the step in the squeeze. Since equation (1) assumes a random noise source, and equation (3) assumes a uniform random noise source, quantitative agreement between observed voltage ripple and emittance growth has not been achieved. On the other hand, relative calculations have been made. A comparison of the data with equation (1) was not possible, since the closed orbit (and hence the magnitude of the dipole kicks in each magnet) was not measured. The horizontal emittance growth rate as a function of the right hand side of equation (3) involved no unknown parameters, and yielded the suggestive result in figure 3.

An inexpensive filter has been designed for the quadrupole power supplies. Assuming the quadrupoles are the dominant source of low-β emittance growth, and taking either the dipole or quadrupole emittance growth models into account, the expected contribution of the BO quadrupoles for the next collider run is less than 0.002 π mm-mrad/hr.

Tevatron RF System

Due to the existence of horizontal dispersion at the RF cavities, phase noise can drive horizontal betatron oscillations. The relationship between emittance growth and rms phase noise, an extension of equation (1), is

$$\dot{\epsilon} = \pi f_o H (eV_o / E)^2 \theta_{rms}^2 \quad , \qquad (4)$$

where E is the beam energy, V_o is the peak RF voltage, θ is in radians, and if η is the dispersion then [12]

$$H = \left[\eta^2 + (\beta \eta' + \alpha \eta)^2\right] / \beta \quad . \qquad (5)$$

During the last collider run RF phase noise was found to cause horizontal emittance growth [8]. Single bunch proton and antiproton phase feedback systems were amplifying the ambient RF phase white noise spectrum, resulting both in increased horizontal oscillation amplitude and emittance growth. The problem was fixed by shutting off those systems.

In March 1988 noise was injected into the Tevatron RF low level phase shifter. Figure 4 contains the result, along with the least square fit to the data. The measured sensitivity of horizontal emittance growth to RF phase noise (degrees) is

$$\dot{\epsilon}_H = (71 \pm 8)\ \theta_{rms}^2 \quad . \qquad (6)$$

This result and a calculation using equation (4) agreed quite well [9]. The expected contribution of the Tevatron RF system to the horizontal emittance growth rate during the next collider run is $<$ 0.006 π mm-mrad/hr. An upper limit is specified since the phase noise of the unmolested system was below the noise floor of the spectrum analyzer.

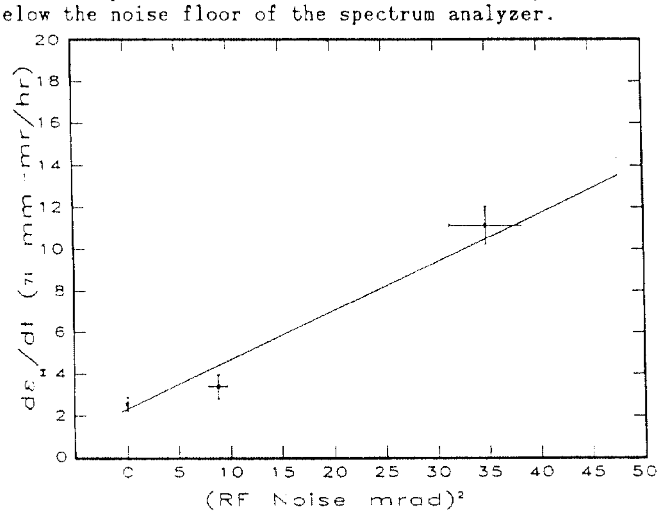

Figure 4: Horizontal emittance growth rate as a function of injected RF phase noise.

Dipole Current Noise

In order to measure the effect of dipole current noise on the transverse emittance growth rate of the beam, common mode voltage noise was superimposed onto the main dipole bus. Since the equivalent circuit for the dipole bus is quite complicated, all common mode filters were eliminated for simplicity sake. Though their relative effect is small, it should be noted that the main quadrupoles are also on this bus.

The horizontal emittance growth rate should be proportional to the square of the power supply noise. Fitting the measured growth rates (π mm-mrad/hr) at a number of noise settings, the power supply common mode voltage noise (Volts) sensitivity is given by

$$\dot{\epsilon} = (1.17 \pm 0.05)\ V_{rms}^2 \quad . \qquad (7)$$

Without filters, the expected horizontal emittance growth rate due to common mode voltage noise for the next collider run is 0.005 π mm-mrad/hr. But at least one set of common mode filters will be added. Using all common mode filters, the expected growth rate would be 1×10^{-7} π mm-mrad/hr.

Next Collider Run

Multiple Coulomb scattering with residual gas causes transverse emittance growth. A calculation of this growth rate in these studies predicts an emittance growth rate of 0.15±0.05 π mm-mrad/hr [13]. This is also the predicted transverse growth rate for the next collider run.

The intrabeam scattering contribution to the horizontal emittance growth rate during the above accelerator experiments should have been 0.10±0.05 π mm-mrad/hr [6]. For the next collider run, since the proton bunch intensity should be the design value of 6×10^{10}, the predicted horizontal emittance growth rate is 0.2±0.1 π mm-mrad/hr.

These two mechanisms should have produced a total emittance growth rate of approximately 0.25 π mm-mrad/hr during these experiments. The minimum emittance growth rate observed was 0.71 π mm-mrad/hr. Therefore, it is likely that other emittance growth mechanisms still exist. A candidate for future study is correction magnet power supply noise.

Conclusions

The transverse emittance growth rate during the next collider run should be almost an order of magnitude smaller than the typical rate observed during recent studies and in the last collider run. The confirmed sources of the past growth were the abort kickers and the RF system. The BO quadrupoles are also growth source candidates.

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