EFFECTS OF RF NOISE ON LONGITUDINAL EMITTANCE GROWTH IN THE TEVATRON*

J. Steimel, V. Lebedev, I. Gonin, T. Khabibouline, J. Reid, G. Romanov, V. Shiltsev, A. Tollestrup, FNAL, Batavia, IL 60510, USA

Abstract

Phase and amplitude noises in the Tevatron RF system and the intrabeam scattering (IBS) produce longitudinal emittance growth with consecutive particle loss from the RF buckets. That causes a decrease of the luminosity and an increase of the background in particle detectors during the store. The report presents experimental measurements of RF system noise and the effect on the longitudinal emittance growth. There is a satisfactory agreement between measured noise spectral densities and observed emittance growth. For high bunch intensities, IBS plays an important role and has been taken into account. The sources of noises and plans for further system improvements are discussed.

INTRODUCTION

One of the major upgrades to the Fermilab Tevatron between Run I and Run II was the increase in the number of colliding bunches by a factor of 6. The total proton intensity was also increased by about the same factor (currently 4.7). In the course of the early commissioning process, the Tevatron would quench every time that 980 GeV beam was aborted with high intensity. Abort kicker timing was inspected and optimized, but the quenches continued.

The quenches are due to beam that has wandered into the abort gap. Measurements show that a line density of somewhere between 3e9 and 9e9 protons distributed around the ring is enough to quench the superconducting magnets on abort. This beam is difficult to measure directly, because its low intensity is below the resolution of the Tevatron DC beam monitors. Only indirect measurements verified the presence of beam in the abort gap until recently. The Tevatron electron lens (TEL) was reconfigured to act as fast pulse kicker in the beam abort gap [1]. The pulse rate was configured to resonate with the betatron tune of the beam to kick beam out of the abort gap. When the lens is activated during a store, there is a sharp loss measured by the DC beam detectors but no effect on luminosity. By turning the lens on and off for different time periods, one could verify DC beam in the abort gap and measure its rate of accumulation.

With confirmation from the electron lens that DC beam was accumulating in the abort gap, we attempted to locate the mechanism for the accumulation. Beam is obviously leaking from the RF bucket, but the mechanism was not obvious. The analysis of the problem has focused on two different mechanisms: intrabeam scattering [2] and noise in the accelerating cavities. The rest of this paper focuses on the experiments and analysis of noise sources in the accelerating system.

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RF NOISE SOURCES

A catalogue of possible sources of noise in the RF system was created in order to trace down possible DC beam generators. Each potential source was measured for noise amplitude, and its possible effect on the beam was analyzed.

Longitudinal Dynamics of RF Noise

In order for beam to spill out of the bucket because of RF noise, there must be beam close to the edge of the bucket separatrix. Beam at high energy in the Tevatron does not fill the bucket initially after the ramp, but the longitudinal emittance increases until the bucket is full. DC beam generation begins when the bucket is full. We assume that the same process that generates DC beam also causes the longitudinal emittance growth. Since we could not measure DC beam directly initially, we measured longitudinal emittance growth to determine the effect that

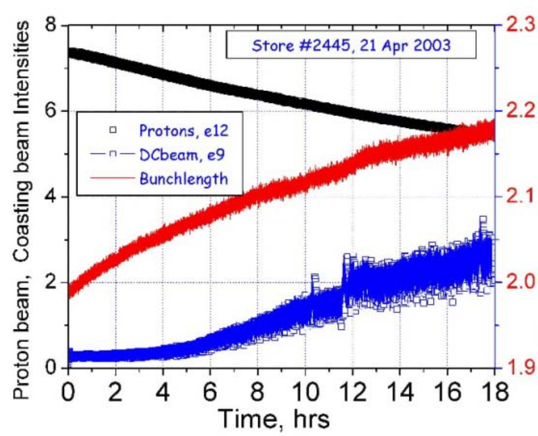

Figure 1: Longitudinal emittance growth and DC beam accumulation vs. time in Tevatron store at 980 GeV.

noise has on beam. The formula for bunch length (σ_ϕ in rms radians) growth in the presence of RF phase noise spectral density ($P_{\phi RF}$ in rms rad^2/Hz) is given in equation (1) where f_s is the synchrotron frequency in Hz [2].

$$\frac{d(\sigma_\phi^2)}{dt} = 2\pi f_s^2 P_{\phi RF}(f_s) \qquad (1)$$

RF Reference Measurements

The first test was to insure that there was not a considerable amount of noise contaminating the reference signal. Measurement of the reference signal using a spectrum analyzer revealed that even the 60Hz spurs were 90dB below the carrier and the noise floor was more than 100dB below the carrier.

RF Cavity Measurements

With the knowledge that the damaging source of RF noise was downstream of the reference, the eight individual cavities were inspected closely. The phase modulation spectrum of each cavity was measured using a phase detector between each accelerating voltage gap monitor and the reference. All of the cavities exhibited a peak in the modulation amplitude from 32-38 Hz, even without beam in the Tevatron. This frequency corresponds to the synchrotron frequency of the Tevatron at 980 GeV.

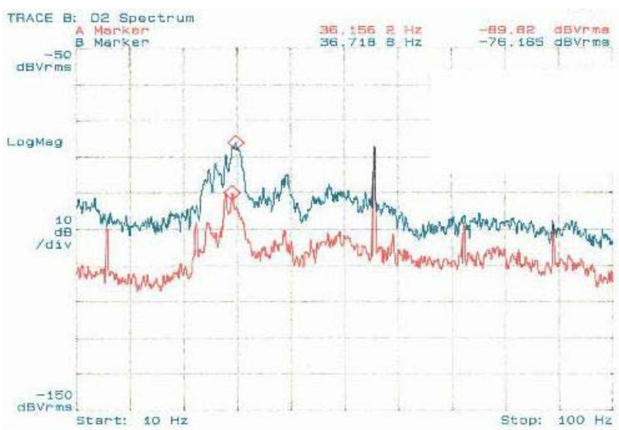

Figure 2: Spectrum of the output of the RF reference to global station fanback phase detector. Top trace is with local station feedback disabled on 3 cavities and bottom trace is with feedback enabled.

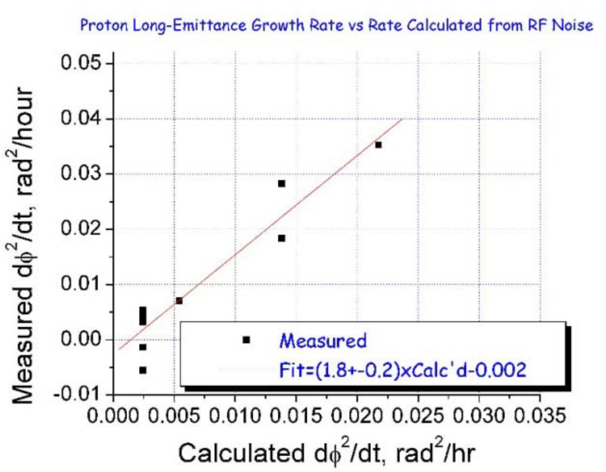

Figure 3: Plot comparing the measured longitudinal emittance growth rate to the emittance growth rate calculated based on the total spectral density of phase noise measured at the synchrotron frequency.

A phase feedback system at each station maintains proper phasing between the gap monitor and reference drive for low frequencies. The gain of this feedback loop was varied for different combinations of cavities. The emmitance growth rate was measured for each gain setting and compared to the noise power measured at the cavities. The intercept of the plot at zero measured cavity noise is very close to the origin. This reveals that the cavity noise is the dominant mechanism for longitudinal emittance growth in the Tevatron at high field.

MECHANICAL MOTION

With data showing that the source of RF noise was somewhere in the cavity system, the next step involved trying to find the specific source. Because the frequency of the modulation is so low and did not correspond to any harmonics of the power cycle, there were suspicions that the cause of the modulation was due to cavity vibrations.

Mechanical Simulations

The central electrode in Tevatron accelerating cavity actually is a pretty long tube beam with rigid supports and links in the middle of it. Such a cantilever beam usually can be a good oscillator (like a piece of tuning fork). A solid model of the central electrode design has been built and a simulation of mechanical vibrations has been performed. The simulated frequencies of mechanical vibrations in a case of copper central electrode are in a close agreement with the measured RF and acoustic noise frequencies. For us it has been a first indication that the central electrode mechanical vibrations may be a cause of RFnoise.

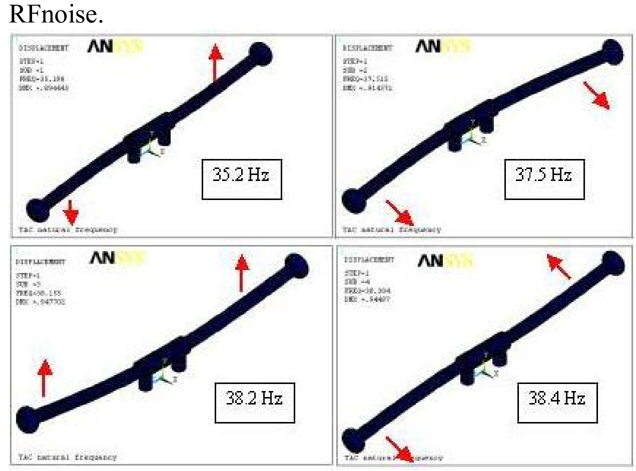

Figure 4: The modes of the central electrode mechanical vibrations.

Effects of Vibrations on RF Noise

A cavity with bent central electrode has been simulated to estimate amplitude of the central electrode vibrations and vibration's influence on RF parameters. Only a half of cavity without transmission line was simulated to increase accuracy of calculations. The curvature of central electrode axis is a regular arc. It seems to be a good enough approximation of small real sinusoidal deformations of electrode during vibrations. Only horizontal deformations have been considered because pick-up electrodes are in horizontal plane and sensitive to these deformations.

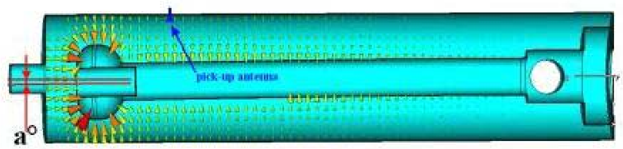

Figure 5: A cavity with bent central electrode.

From the RF noise point of view two cavity parameters are important: 1) modulation of resonant frequency of cavity that produces amplitude and phase modulation of accelerating field, and 2) electric field level modulation in pick-up electrode area. The latter has nothing to do directly with particle acceleration, but it is very important as the only signal for the feedback systems. Equation (2) shows the empirical relationship between resonant frequency shift and electrode bend angle.

$$\Delta f = a\theta^2 \qquad (2)$$

Modulation of cavity resonant frequency produces modulation of phase and amplitude of electromagnetic field oscillations. The sensitivity of resonant frequency to the central electrode bend is low around zero bend point and resonant frequency modulation does not seem to be a problem in a case of perfect axial symmetrical cavity. But the central electrodes can have "natural" bends in any plane that could occur during manufacturing and installation. An estimation for phase shift enhanced by initial permanent central electrode bend is given in (3), where Θ is an initial bend angle, θ is a small bend deviation the initial bend angle. Q is the cavity quality factor, and "a" is the empirically determined factor from equation (2). For the Tevatron cavities this value was calculated to be 79 kHz/degree^2.

$$\varphi \approx \frac{2Q(2a\Theta\theta + a\theta^2)}{f} \qquad (3)$$

Amplitude modulation due to the field level variation at pick-up electrode area seems to be predominant at normal operating conditions. Amplitude modulation is transformed into phase modulation in a phase feedback loop, because even an ideal linear phase-lock loop system can generate phase noise responding to amplitude modulation of input signals.

Measurements of Vibrations

Four geophones were installed at opposite ends of a Tevatron test cavity, two in the horizontal plane and two in the vertical plane. The spectrum measured from the sensors on the test cavity, with water pumps and heaters on, match the noise spectrum measured on the operating cavities. The experiment was repeated with water pumps and water heaters disabled, and the 37Hz modulation was significantly reduced. Measurements of vibrations on the operating cavities revealed the same relationship between the modulation and the water pumps. Thus, the water pumps act as the drive for the cavity mechanical resonance.

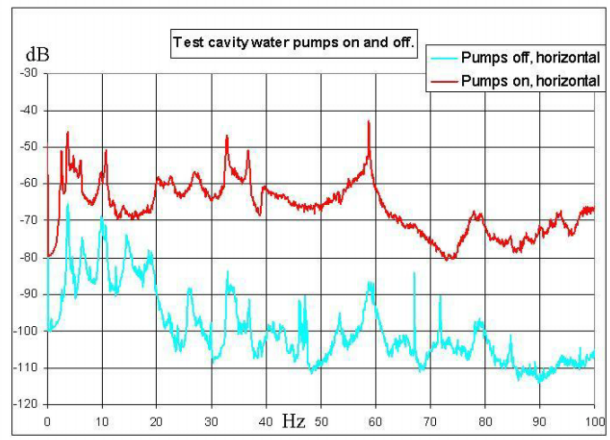

Figure 6: Comparison of mechanical vibration spectra with and without water pumps.

CONCLUSIONS

There is very strong evidence that the mechanical vibrations of the Tevatron RF cavities cause longitudinal emittance growth and accumulate DC beam. We plan to try methods to decrease vibrations during the collider operation:

- Remove sources of mechanical vibrations. For example, insulate water heaters from cavities mechanically.
- Use two pickup antennae from the cavity and combine these signals to reduce amplitude modulation due to cavity warping.
- Implement direct RF feedback around each individual station.

REFERENCES

[1] X. Zhang, et al, "The Special Applications of Tevatron Electron Lens in Collider Operation," PAC '03, these proceedings.

[2] V. Lebedev, "Beam Physics at Tevatron," PAC'03, these proceedings