A Test of Bunched Beam Stochastic Cooling in the Fermilab Tevatron Collider

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Abstract

In order to double the integrated luminosity of the Tevatron collider in the next running period, a 4-8 GHz bunched beam betatron stochastic cooling system has been designed. The horizontal and vertical emittances of the protons and antiprotons will be cooled to counteract the effects of power supply noise, beam-beam interaction, and intrabeam scattering. A vertical proton test system has been installed in the Tevatron and tested. In addition to measurement results, details of the hardware and cooling calculations are reviewed. Improvements coming from experience with this test configuration are being incorporated into the construction of the full system.

I. INTRODUCTION

In order to specify the requirements for the stochastic cooling system, the effect of emittance damping on luminosity lifetime [1] was explored [2]. If proton and antiproton horizontal and vertical emittance cooling was implemented with an average time constant of approximately 20 hours, the integrated luminosity of the next collider run should double.

The basic equation describing the optimum emittance cooling time is

$$\tau_\varepsilon = T_0 N_s (M + U) \quad , \qquad (1)$$

where T_0 is the revolution period, M is the mixing factor, U is the noise power to signal power ratio, and N_s is the number of protons per bandwidth sample. Calculations of the bunched and unbunched betatron spectra suggest that the mixing factor should be the same under both conditions. This hypothesis was confirmed by experiments in the Accumulator ring [3].

At an RF voltage of 800 kV/turn the rms bunch lengths and fractional momentum spreads are 2 nsec and 1.5×10^{-4} at 900 GeV. The horizontal and vertical invariant 95% emittances are approximately 20π mm-mrad. Assuming a cooling bandwidth of 4-8 GHz and the expected beam intensity and longitudinal emittance values of 7×10^{10} and 5 eV-sec, the expected average mixing factor and sample intensity are 4.5 and 1×10^{9}. Since the noise to signal power ratio is negligible and the revolution frequency period is 20.94 μsec, the calculated emittance cooling time is 26 hours.

II. PROTOTYPE SYSTEM DESIGN

A prototype vertical proton stochastic cooling system was designed and installed in the Tevatron near the F0 warm straight section. Due to technical, fiscal, and ecological concerns, it was not feasible to build a classical stochastic cooling feedback loop where the signals from the pickup to the kicker cut a chord across the ring. Instead, this system uses an optical delay line between the adjacent pickup and kicker. The physical separation of the pickup and kicker is approximately 60 m to provide a $\lambda_\beta/4$ fractional betatron tune advance for optimal cooling rate.

The pickup and kicker are composed of two moveable plates, each supporting an array of 16 coplanar loops [4]. The loops are actually etched images on a teflon circuit board. The signals from the 16 loops are combined on the reverse side of the board. The combined signals from each plate are brought outside the tank and are immediately subtracted by a 180° hybrid. After 35dB of gain from a low noise preamplifier (which is the only active circuit element in the tunnel), the difference signal is sent to the F0 RF building.

After more amplification the signal goes through a fast pin diode switch for signal gating at the RF bucket level. The absolute necessity of this switch will become apparent in the discussions later in this paper. This gate is followed by a transfer switch and the modulation input of the optical fiber delay line laser driver. The transfer switch is used to perform open loop transfer function measurements vital for system timing and gain adjustments, and is also a convenient location to monitor beam signals. The fiber optic delay line is in a temperature controlled chamber to provide the required picosecond level timing stability. Finally the signal is amplified by a traveling wave tube and sent to the kicker. The kicker tank and electrodes are identical to the pickup.

III. PRELIMINARY MEASUREMENTS

A. Without Beam

Measurements were initially performed without beam [5]. Spectral harmonics of the spikes generated by the class C power amplifiers of the Tevatron RF cavities [6] were observed to be transmitted down the beam pipe and received by the pickup, which was approximately 10 m away from the nearest cavity. By changing the grid bias to widen the current pulses, it will be possible to eliminate these unwanted signals.

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Since the beam pipe acts as a microwave waveguide in the 4-8 GHz frequency band the pickup and kicker are able to close the feedback loop without beam. This caused an instability since the loop gain was greater than unity. The solution to this problem, whose severity depended on the aperture between the opposing arrays, was to install the bucket gating switch. Allowing only the signals from the 6 out of 1113 RF buckets to be amplified, the delay between the kicker and the pickup made positive feedback amplification impossible.

The bucket gating switch also had a beneficial effect on passive spectra and transfer function measurements. By gating the signal after the initial stages of amplification, only a fraction of the thermal noise power makes it to the input receivers of the spectrum and network analyzers. Therefore the signal to noise of those measurements improved by the ratio of the revolution period to six times the gate width, approximately a factor of 100.

B. Passive Spectrum

An example of a passive spectrum measurement is shown in figure 1. There are four distinct features to the spectrum. First and foremost, the vertical Schottky betatron lines are clearly visible as broad distributions rising 7dB above the noise floor. Since the vertical betatron tune was approximately 0.41, the upper and lower sidebands are close together. The observation of these Schottky signals is a very encouraging sign for the success of this project.

At the frequencies corresponding to three revolution harmonics, the very strong coherent beam signals almost wash out the longitudinal Schottky bands, which rise above the noise floor by about 10dB. These coherent signals can be 50dB higher than the betatron Schottky signals, causing a serious dynamic range problem in the amplifier chain.

C. Transfer Functions

A number of transfer function measurements have been performed to time the system in preparation for cooling studies. Though the cooling studies did not occur, much was learned about the response of the system and the beam. Figure 2 contains an example of such a transfer function measurement, where four full revolution harmonic bands are visible. The betatron lines stand out quite clearly, and the phase responds as expected.

The feature which distinguishes a bunched beam response function from a coasting beam transfer function measurement is synchrotron sideband structure. It usually appears as a region of noise in the amplitude and phase near the peak of a betatron resonance. Figure 3 contains a transfer function measurement of a single pair of betatron lines which exhibits this structure. The synchrotron sidebands of the betatron tune appear in this region since the lower order sidebands are relatively narrow and can be resolved independently from their neighbors. Note that these betatron peaks are readily visible at 4 GHz, whereas at 8 GHz they form an almost uniform signal floor with the help of the broader longitudinal Schottky bands.

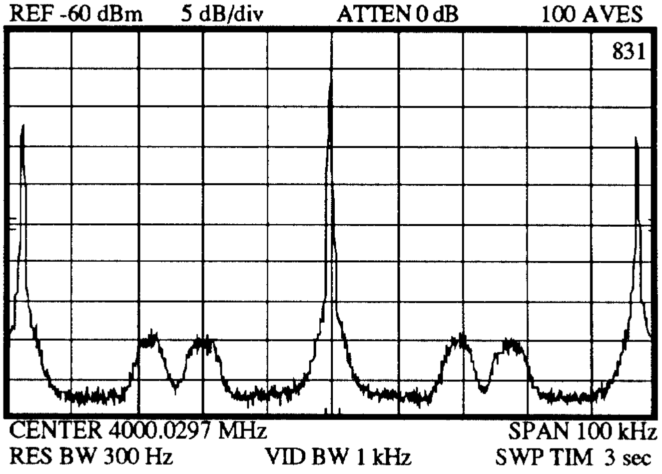

Figure 1: Typical Tevatron vertical bunched beam spectrum as measured by the vertical proton pickup. The intensity was 3.3×10^{10} per bunch and the beam energy was 900 GeV.

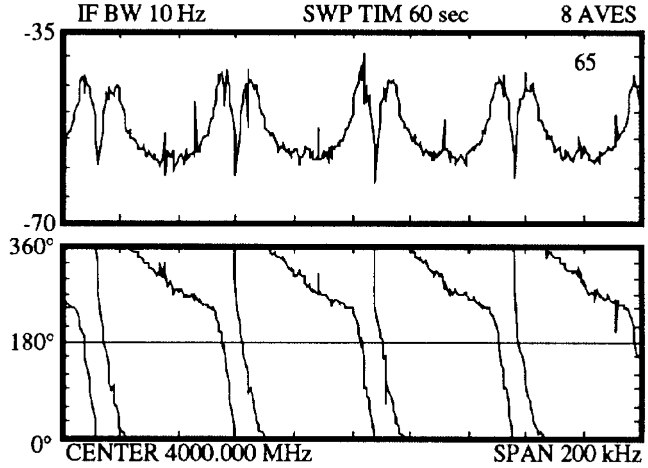

Figure 2: Multiband transfer function measurement of the cooling loop with beam. The bunch intensity was 3.1×10^{10}.

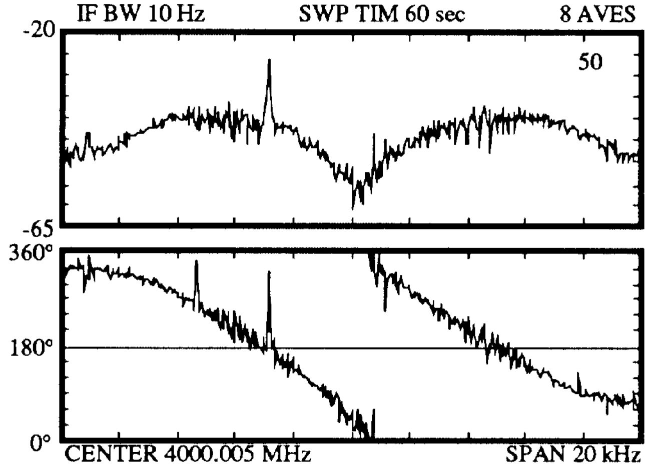

Figure 3: Closeup of a pair of betatron lines. The sharp spike in the left betatron line was caused by a head tail instability when the chromaticity of the Tevatron drifted negative.

In order to properly time the system, the phase of the beam response in the null between these regions of synchrotron sideband structure must be set to 180° over the entire 4-8 GHz frequency octave. A combination of system delay adjustment and equalizers will be utilized in the future.

D. Microwave Instability

A major concern during the planning for this system was the existence of propagating microwave modes associated with the beam dominating the signal measured by the pickup. During commissioning of the vertical proton prototype system such modes were indeed observed. The measurement was performed by replacing the spectrum analyzer with a Tektronix 11802 sampling oscilloscope. With a 20 GHz bandwidth SD-24 sampling head, this scope was capable of observing the beam signal from the pickup in the time domain. One of the more convenient data acquisition modes for monitoring the beam signal was the envelope function, which stored the minimum and maximum voltage in each sampling bin across the screen. Figure 4 contains 3 such traces. The bucket gating system was disabled during these measurements, and the travelling wave tube driving the kicker was turned off.

Just after injection into the Tevatron, the beam signal is completely washed out by a microwave burst which decays with an apparent time constant of roughly 100 nsec. After approximately 30 minutes of sitting at 150 GeV this burst suddenly disappears, leaving behind only the Schottky and coherent signal of the beam. Figure 4 shows the typical time sequence of this phenomenon. Note that the bunch is centered on the second division from the left (see bottom trace). In the 4 minutes between the last two frames, there was no warning that the microwave burst was about to disappear. The value of 0.3 volts, which is the upper and lower limits of the vertical scales of the oscilloscope traces, represents the output saturation level of the preamplifier chain. The actual microwave signals are probably much larger.

At present the source of these microwave modes is not understood. The hypothesis at the moment is that the coalescing process generates bunches with a large amount of high frequency phase space structure. This high frequency component of the current interacts with a resonator upstream of the pickup, and a voltage is produced. Since the burst of microwave modes disappears suddenly, it is probable that the bunch is actually microwave unstable, enhancing the current modulation and hence the voltage in the beam pipe. Once the momentum spread of the bunch has increased sufficiently, the instability is stabilized and the voltage drops dramatically. Clearly, many more measurements are required before this signal is understood and the problem is corrected.

IV. FUTURE WORK

Presently the coherent component of the beam signal is saturating all of the amplifiers (with perhaps the exception of the preamplifier in the tunnel). Work is presently underway to replace the 180° hybrid to improve common mode rejection, and studies are planned to understand the cause of these anomalously large coherent signals associated with such a long bunch. A comb notch filter is being designed to suppress the coherent revolution harmonic power, but it may have serious dynamic range problems itself.

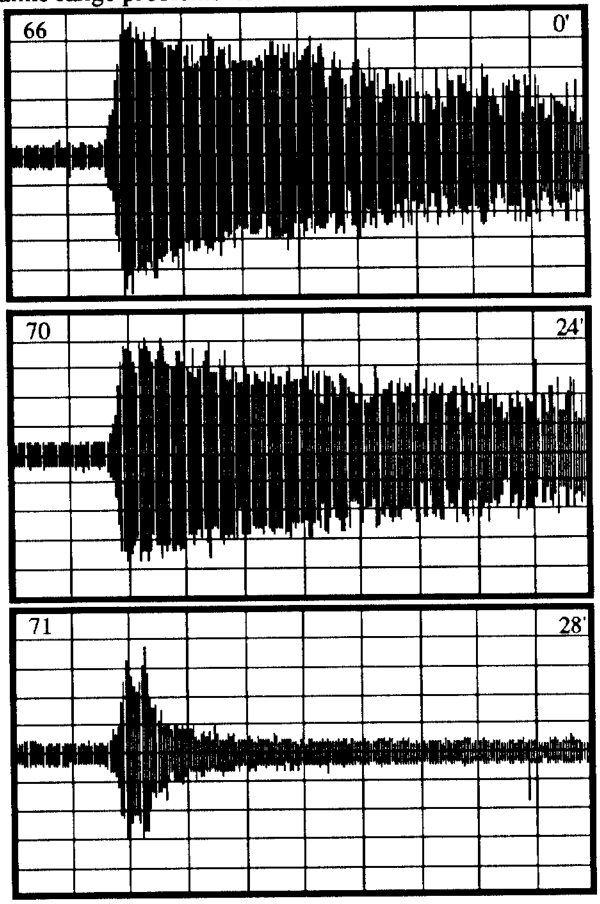

Figure 4: Sampling oscilloscope traces of the pickup signal voltage as a function of time. The scales are ±0.3 volts full scale vertically and 20 nsec/div horizontally. The numbers in the upper right corners is the time since injection.

V. REFERENCES

1. G. Jackson, "Winter 1988 Luminosity Lifetime Studies Analysis Results", internal Fermilab memo EXP-154 (1988).
2. G. Jackson, "Bunched Beam Stochastic Cooling", Proc. IEEE Part. Acc. Conf., San Francisco (1991).
3. J. Marriner, G. Jackson, D. McGinnis, R. Pasquinelli, D. Peterson, J. Petter, "Bunched Beam Cooling in the FNAL Antiproton Accumulator", Proc. Eur. Part. Acc. Conf., Nice (1990), p. 1577.
4. D. McGinnis, J. Budlong, G. Jackson, J. Marriner, and D. Poll, "Design of 4-8 GHz Bunched Beam Stochastic Cooling Arrays for the Fermilab Tevatron" Proc. IEEE Part. Acc. Conf., San Francisco (1991).
5. G. Jackson, J. Marriner, D. McGinnis, R. Pasquinelli, and D. Peterson, "Bunched Beam Schottky Signal Measurements for the Tevatron Stochastic Cooling System", Proc. Adv. Instr. Workshop, KEK (1991).
6. Q. Kerns, et al., "Energy Saver Prototype Accelerating Resonator", IEEE Trans. Nucl. Sci., Vol. NS-28, No. 3 (1981), p. 2782.