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 prototype system has been installed in the Tevatron and tested. In addition, measurement results and details of the hardware are reviewed.

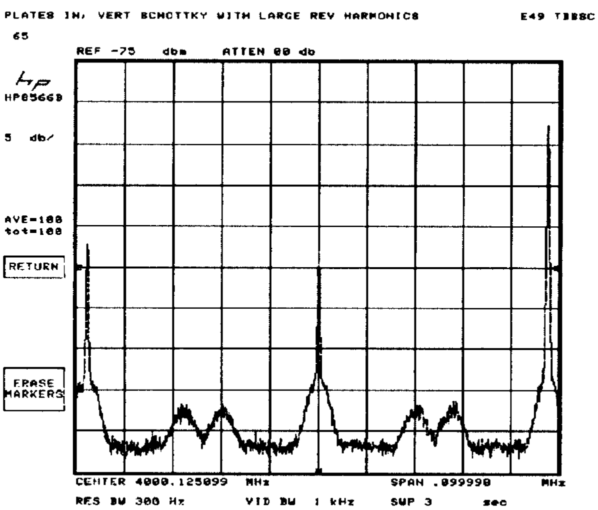

Figure 1: Measured beam spectrum from a vertical proton pickup. Note the large coherent lines at revolution harmonic frequencies at the left, center, and right. The betatron Schottky lines are clearly visible above the noise floor. The center frequency is 4 GHz and the scale is 10 kHz/div.

I. Introduction

A great deal of measurement, calculation, design, and construction work has gone into the Tevatron bunched beam stochastic cooling system [1] in the last two years. Based on beam measurements made with the first proton vertical cooling system [2], a second pickup tank was fabricated with improvements aimed at solving the problem of large revolution harmonic power saturating amplifiers (see figure 1). In addition, a new repetitive notch filter was designed and built [3] to further combat the power at harmonics of the revolution frequency. System phasing and timing adjustments have been completed.

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II. Coherent Power Measurements

One of the mysteries associated with bunched beam cooling in the Tevatron Collider was the existence of larger than expected coherent revolution harmonic power. Given that the longitudinal distribution of the beam is roughly Gaussian [4], one would expect that the revolution harmonic power should drop quadratically when viewed on a logarithmic scale. Figure 2 contains the measured revolution harmonic power as a function of frequency (where the beam power at each harmonic of the RF frequency was measured). Note that instead of a downward parabolic shape, the spectrum actually exhibits something like a 1/f shape.

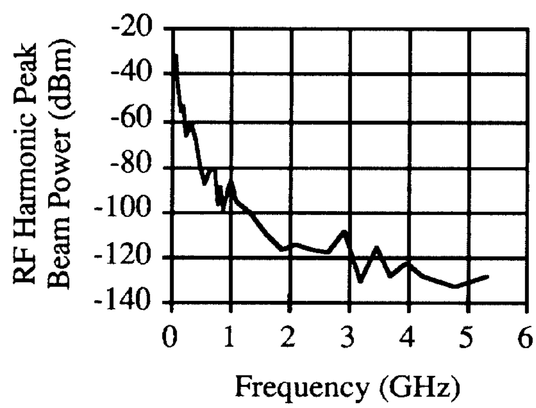

Figure 2: Beam current power spectrum, measured at each harmonic of the RF frequency.

If one were to Fourier transform this distribution back into the time domain, the required beam profile would scale as the K_1 Bessel function, which is undefined at the bunch center! Therefore, this excessive power at high frequency must be due to a small, high frequency modulation of the beam profile. This high frequency structure could possibly be due to filamentation from a small coherent oscillation [5].

A study was undertaken to find such a coherent oscillation. Figure 3 contains a closeup view of a revolution harmonic line. By fitting the amplitudes of the various synchrotron sidebands on either side of the revolution frequency to a Bessel

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function distribution describing FM modulation, a coherent dipole oscillation of amplitude 60 psec is calculated. Therefore, a plausible explanation for these lines now exists.

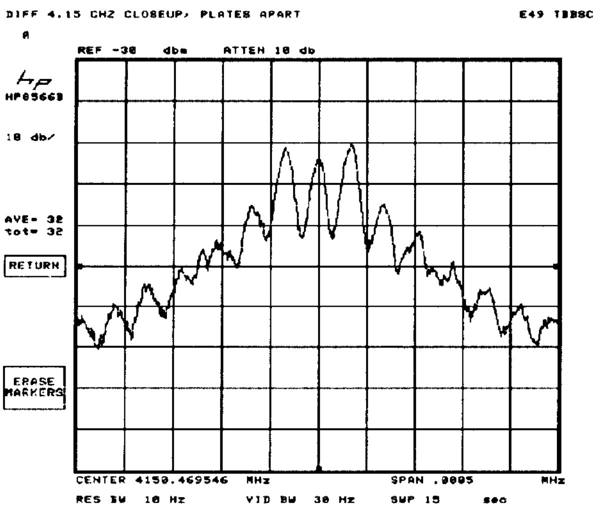

Figure 3: Closeup of the power spectrum of a single revolution harmonic line near 4.15 GHz. The frequency scale is 50 Hz/div.

III. Prototype Pickup Improvements

In order to balance the phase from the top and bottom detector arrays, both a Petter hybrid [2] and a Burleigh inchworm motor [6] were installed to adjust their relative vectorial alignment. The inchworm motor, which has a step size of 1 micron, was required because a longitudinal misalignment of the plates as small as 60 microns could ruin the common mode rejection required to suppress the coherent revolution harmonic power.

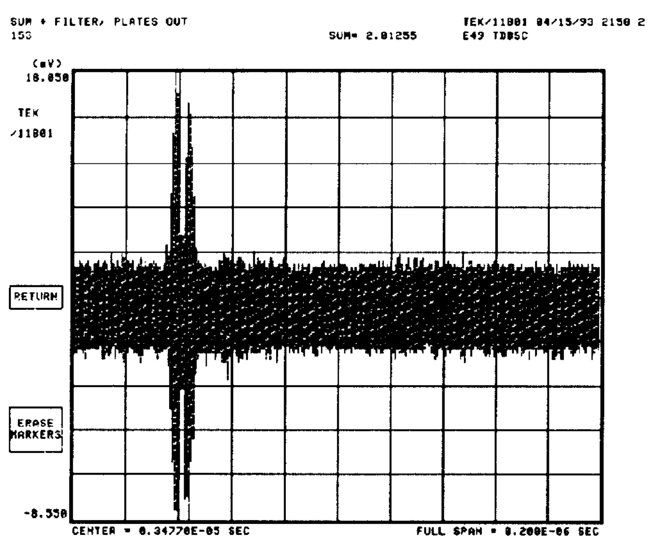

Figure 4: Max/min hold sampling oscilloscope image of the sum signal from the 180° hybrid. The time scale is 20 nsec/div.

With the original pickup array it was noted [2] that microwave signals trailed the bunch signal on an oscilloscope image of the pickup signal. This microwave burst was found to be caused by the response of the tunnel preamplifier to shock excitation by a large voltage burst of beam signal. With the above improvements reducing the coherent power (and hence voltage), this phenomenon is no longer visible (see figures 4 and 5). What remains is a small microwave signal on only the hybrid difference port which is independent of coherent beam power.

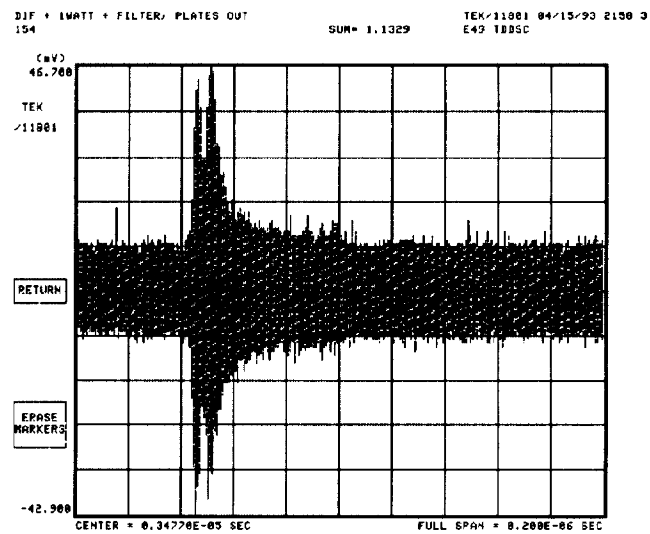

Figure 5: Max/min hold sampling oscilloscope image of the difference signal from the 180° hybrid. The time scale is 20 nsec/div. Note the small amount of microwave power trailing the beam signal which is still present in the new prototype.

III. Repetitive Notch Loop Filter

A typical single turn delay notch filter produces a |sin(x)| response which repeats each revolution period. The unfortunate aspect of this filter is that the phase linearly progresses through 180° every revolution period. In the case of small mixing factor where the betatron Schottky signals are spread over a large portion of each revolution band, a large portion of the particles see either no damping or antidamping.

The purpose of the loop notch filter is to overcome this phase change per band. The phase change comes from the fact that betatron oscillation information is being applied to the kicker one turn too late, thereby giving the particles the wrong kick. If one injects a bunch signal into a storage loop each turn, where the fraction of the signal which survives one turn of the loop is described by the variable α, the betatron information is exponentially averaged away and the transfer function of the full filter becomes

$$T(\omega) = \frac{1 - e^{-i\omega\tau}}{1 - \alpha e^{-i\omega\tau}} \quad , \qquad (1)$$

where τ is the revolution period (see figures 6 and 7).

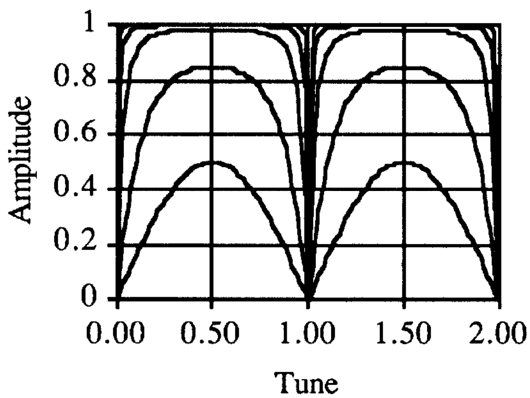

Figure 6: Calculated amplitude response of a loop notch filter. The lowest curve is for the limiting case of a single turn delay notch filter (α<<1). The value of 1-α for the other curves are 0.3, 0.1, 0.03, and 0.01 (in order of progressively improved notch width and phase change filter characteristics).

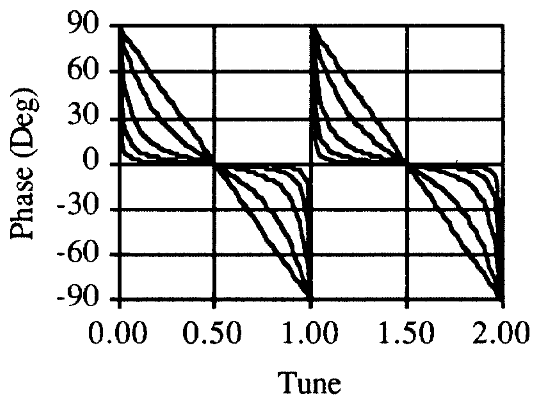

Figure 7: Phase corresponding to the above amplitudes. The straight diagonal lines are in the limiting case of a single turn delay notch filter.

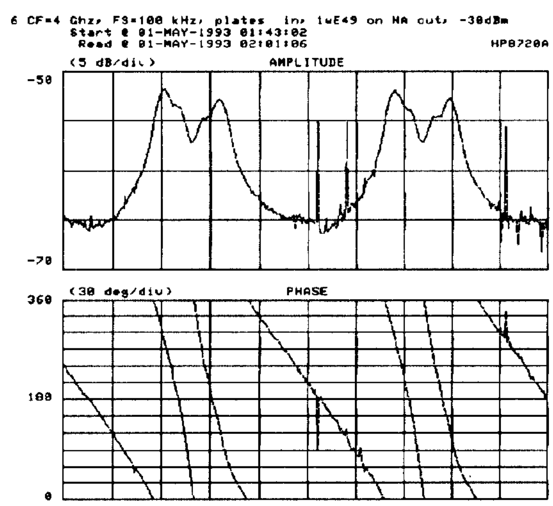

Figure 8: Open loop transfer function measurement across two revolution harmonic bands at 4 GHz. Note the phase rolls through 3x360° per band.

IV. Phasing & Timing Measurements

When the second prototype pickup tank was installed, the relative position of the pickup and kicker tanks in the lattice was reversed (pickup now upstream). This was done because the fractional tune of the accelerator was changed from 0.4 to 0.6, and the change was necessary to keep the phase advance between the pickup and kicker at an odd multiple of 90°. The implications of this change on open loop transfer function measurements was both dramatic and unexpected (see figure 8).

Compared with the previous measurements [2], which exhibited a destructive interference in the amplitude at a fractional tune of 0.5, the amplitude at that point now adds the signals from both betatron lines. In the phase, while previous measurements showed a phase advance of 2x360° per revolution harmonic band, 3x360° is now observed.

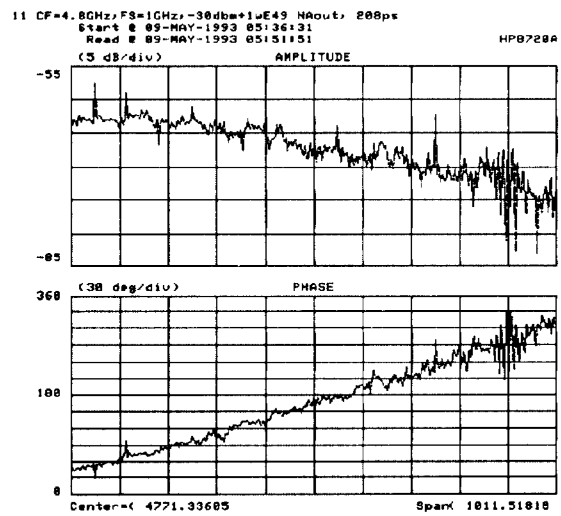

Figure 9: Timing measurement where the phase and amplitude at a fractional tune of 0.5 is measured every 205 revolution harmonic bands with a center frequency of 4.77 GHz. The phase slope indicates that the electrical length is too short.

V. References

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