TUNE SPECTRA IN THE TEVATRON COLLIDER

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Abstract

A variety of transverse and longitudinal tune studies have been made in the Tevatron with both single and colliding beams. Besides measuring such typical quantities as tunes and chromaticity, beam-beam tune shifts and coherent beam-beam normal mode oscillations have been observed. A number of measurements are reported where the beam response to stimulation is studied.

Motivation

During the present Fermilab colliding proton-antiproton physics program Tevatron luminosity has been limited by the beam-beam interaction. At the injection energy of 150 GeV the antiproton bunch intensity lifetimes and transverse emittance growth rates are critically sensitive to the proton bunch emittances and intensities. In addition, luminosity lifetime is also sensitive to these conditions. It is therefore important to measure and understand the antiproton tune distribution.

Tevatron Conditions

The data in this paper was acquired when the Tevatron [2] was either at 150 GeV or at the colliding beam physics energy of 900 GeV. In both cases either there were only protons circulating (a sample spectrum is shown figure 1) or 6 proton bunches colliding with 6 antiproton bunches (see figure 2).

The tuned 21.4 MHz detector [3] which measured the betatron spectra in figures 1 and 2 was designed to be sensitive enough to measure the Schottky [4] power of the beam. The output of sensitive receivers [5] is fed into HP 3561A Signal Analyzers. It is the result of this processing which appears in the figures. Unfortunately, the existence of noise at betatron sideband frequencies produces a subsequent beam response with much greater power than the Schottky signal. For instance, most of the narrow spikes in figure 2 are due to a comb of 60 Hz frequencies applied across the proton tune distribution, probably at the lowest betatron sideband around 19 kHz. Figure 3 shows a much better example of the effect of modulated power supply ripple on the beam.

For tune measurements in which the response of a bunch to a known excitation is required, a system called the Tevatron superdampers [6] exists. It is capable of applying an external signal to its deflection plates to a particular bunch in either the horizontal or vertical plane.

The harmonic number of the RF system is h=1113, and there are 6 bunches per beam. Since 1113 is not evenly divisible by 6, the proton and antiproton bunch intervals oscillate between 185 and 186 RF buckets. This makes the analysis of bunch spectra quite complicated, since for equal intensities the coherent revolution and betatron spectra are modulated. Figure 4 contains an example spectrum showing this effect.

Chromaticity

The classic way to measure chromaticity is to vary the RF frequency, and hence the beam energy, and measure the change in the tune. When there are only protons circulating in the accelerator it should be possible to calculate the chromaticity from the ratio of the power in the synchrotron sidebands around the betatron tune. Assume that a proton bunch is kicked once transversely, exciting all frequencies equally. In the case of protons in the Tevatron, chromaticity coupled with momentum oscillations create a comb of synchrotron sidebands around the betatron line. The rms amplitude of each sideband m is given by [7]

$$A_m = A_o \exp\left(-\sigma_\delta^2 \xi^2 / \nu_s^2\right) I_m\left(\sigma_\delta^2 \xi^2 / \nu_s^2\right) \quad , \quad (1)$$

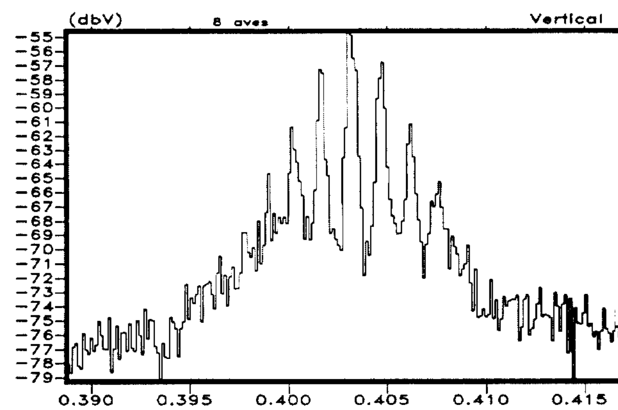

Figure 1: Vertical single beam spectrum at 150 GeV. The vertical scale is in decibels with respect to 1 volt, the horizontal scale is in units of tune.

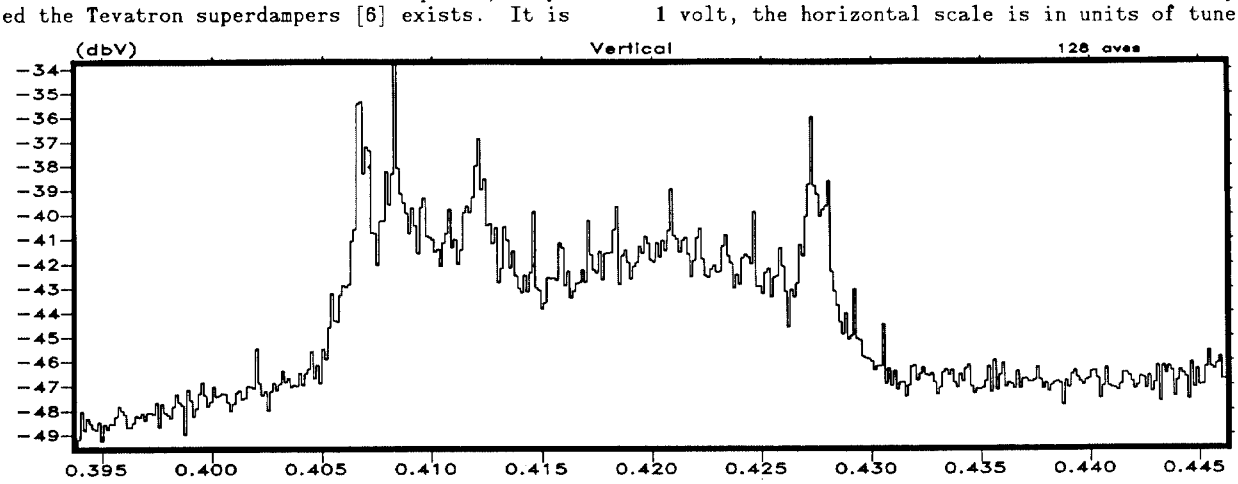

Figure 2: Vertical colliding beam spectrum at 150 GeV.

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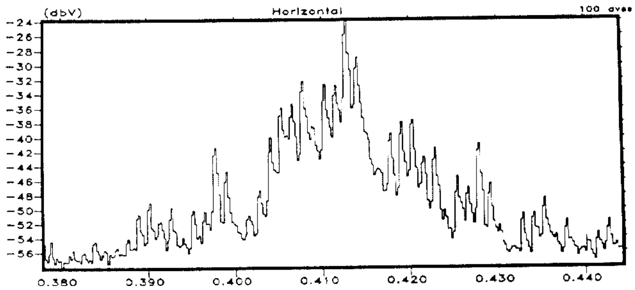

Figure 3: Measurement of the beam response to a modulated 60 Hz comb of frequencies across a betatron sideband. Note that approximately every 5th sideband is missing. The cause of this noise was identified as an injection device power supply.

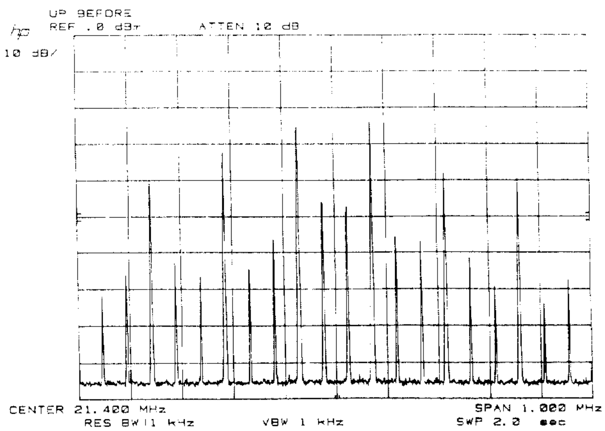

Figure 4: Measurement of the coherent revolution harmonic lines from 6 protons when the beam does not traverse the center of the Schottky detector. The center of the plot is the tune of 448.5.

where σ_δ is the rms fractional energy spread of the bunch, ξ is the chromaticity, ν_s is the synchrotron tune, and I_m is a modified Bessel function.

For the conditions under which figure 1 was taken, the chromaticity extracted using equation 1 was compared against an RF frequency/tune change measurement. Equation 1 yielded a chromaticity of 6.0 units, and the RF frequency/tune change measurement found a chromaticity of 6.5, a difference of 10%.

Synchrotron Plane

In the above section on chromaticity, a parameter which was needed in order to solve equation 1 for chromaticity was the synchrotron tune. Using a bunch by bunch phase detector/damper [9], the synchrotron tunes of the protons and antiprotons were studied. An example of an antiproton synchrotron tune measurement is shown in figure 5. The expected Schottky amplitude, which is proportional to the bunch length divided by the square root of the number of protons per bunch, is much smaller than this observed signal. Time and frequency analysis of the relative proton and antiproton phases show protons oscillate together in phase and with the same amplitude. Antiproton bunches behave similarly. On the other hand, proton and antiproton synchrotron motions are not correlated.

Beam-Beam Normal Modes

Ignoring the narrow 60 Hz spikes in the spectrum in figure 2, note that there are three broader peaks around 0.410, a peak up at 0.428, and a broad response band in between. From this observation, and data when the beam sizes are modified [8], it is clear that the peaks are coherent beam-beam normal modes [10] previously observed in e+e- accelerators.

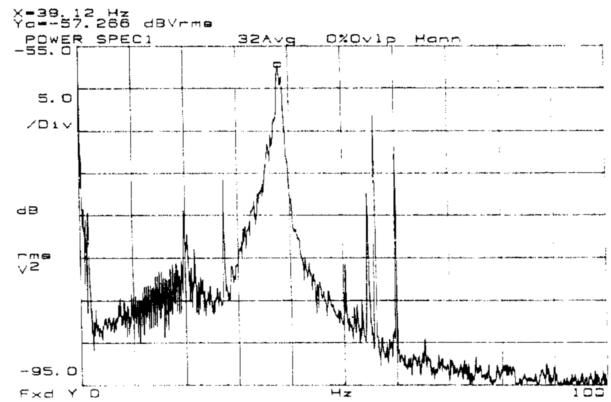

Figure 5: Example of the synchrotron spectrum of an antiproton bunch at 900 GeV. The scales are 5 dbm and 10 Hz per division. The distribution peaks at 38 Hz.

Driven Response

Since the antiproton intensity is usually around one third of the proton intensity, a potentially powerful tool for measuring antiproton tunes independent of their proton counterparts is through the transverse excitation of a single antiproton bunch. Using an HP 3577A Network Analyzer, the superdamper system, and the Schottky detector, the transfer functions of the beams were measured. The remainder of this paper is devoted toward betatron tune measurements with this system.

Coupling

Since the horizontal and vertical emittances of the beams are roughly equal, not much attention is paid to the coupling [11] in the Tevatron. Unfortunately, the

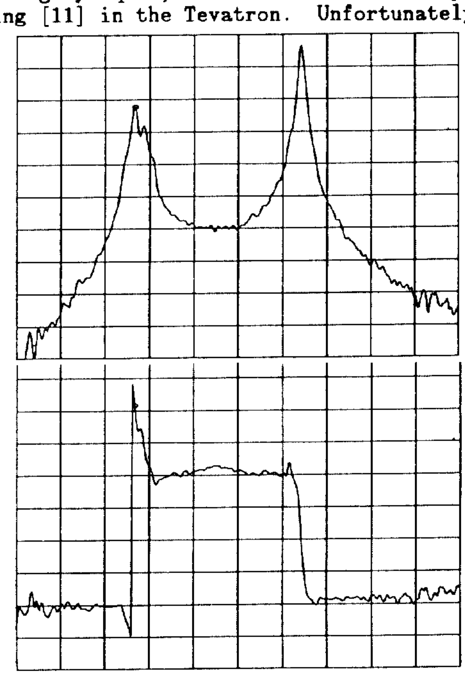

Figure 6: Measured horizontal betatron response to a swept frequency vertical sine wave excitation. The top plot is the amplitude response at 5 dbm/div, the bottom plot is the relative phase of the response at 45 deg/div. The frequency scale is 200 Hz/div.

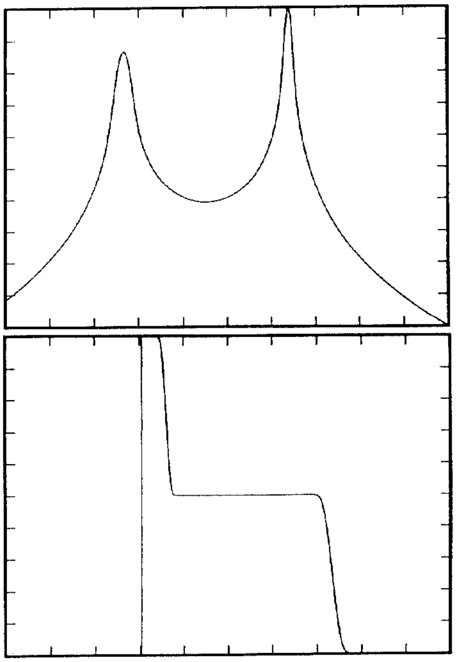

Figure 7: Simulated horizontal betatron response to vertical excitation. The vertical scales are 5 dbm (top) and 36 degrees (bottom) per division.

Tevatron is run very near the coupling resonance, so the separation of the horizontal and vertical tunes is dominated by coupling tune shift. The goal of this work is to measure the tunes of the antiprotons under operationally relevant conditions, so an effort must be made to understand the tune distributions in the presence of substantial coupling.

In contrast to the single beam spectrum shown in figure 1, when the calculated linear beam-beam tune shift [12] of the protons due to the antiprotons is less than 0.01, the proton tune distribution appears to be roughly Gaussian. When the swept sine wave from the network analyzer is driven through the tunes of a proton bunch in such a situation, the response is similar to the example shown in figure 6.

Using the solution of a driven harmonic oscillator and the theory of weak coupling [13], the expected response of a beam in a coupled lattice to a sine wave at an arbitrary frequency has been calculated. Using the measured line widths, tune separations, and amplitudes in figure 6, the expected amplitude/phase response is shown in figure 7. Allowing for the fact that the phase curves wrap around ±180° at different frequencies, the agreement is quite good.

Antiproton Tune Deconvolution

At 900 GeV when 6 proton and 6 antiprotons are in collision a single antiproton bunch was excited horizontally with the network analyzer. Figure 8 shows the horizontal amplitude/phase response. Note the two broad amplitude peaks with long response tails to either side. These tails are due to the typical Lorentzian response of a driven harmonic oscillator.

Of interest is the tune density distribution which caused this response. The deconvolution of the harmonic oscillator response from the measured data is accomplished by multiplying each amplitude bin by the cosine of the phase of each bin. The result of this operation is shown in figure 9. The smaller peak corresponds to the proton tune, where the excitation of proton motion was induced by beam-beam interaction coupling from the antiproton motion. The larger peak represents the antiproton tune distribution. The lines are at the 2/5, 5/12, and 3/7 resonances.

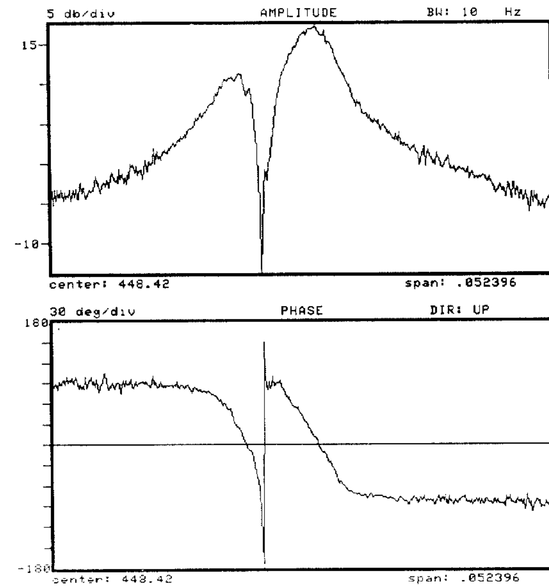

Figure 8: Measured horizontal response of 6 proton and 6 antiproton bunches to the horizontal excitation of one antiproton bunch.

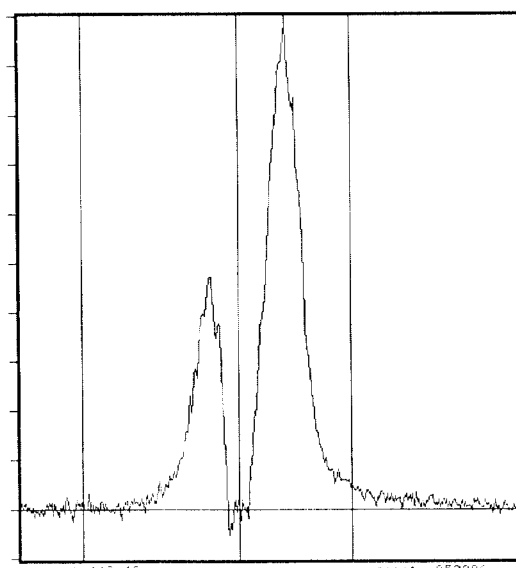

Figure 9: Calculated tune density distribution which produced the transfer function in figure 8.

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