Results from Longitudinal Impedance Measurements in the Fermilab Tevatron

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Abstract

In order to answer questions concerning performance limitations in future accelerator upgrade scenarios caused by coherent instabilities, a considerable amount of effort has been devoted to impedance measurements. This work presents the results from beam-based longitudinal impedance measurements in the Tevatron. Longitudinal transfer function scans with high current unbunched beam at injection is the method used for determining the impedance at every revolution harmonic. Self-bunching instabilities and wave-mixing phenomena occurring during these transfer function measurements are also described. While presenting results, methods to minimize noise and systematic errors are reviewed.

I. EXPERIMENTAL METHOD

By sinusoidally modulating the current of a coasting beam the longitudinal impedance may be measured at any frequency corresponding to a harmonic of the revolution frequency [1,2]. This technique, in the form of a longitudinal closed loop transfer function measurement, has been applied to the Tevatron in an attempt to accurately map the longitudinal impedance as a function of frequency. A sketch of the experimental equipment is displayed in figure 1. The spectrum analyzers are used to measure the longitudinal Schottky distribution and to monitor "ghost" lines (wave-mixing).

After injecting 972 bunches into the 1113 53 MHz RF buckets at 150 GeV the RF voltage was adiabatically reduced by paraphasing two sets of four cavities. When the minimum voltage was attained, the RF power amplifiers were turned off. This beam could then be studied for up to a day.

Because of the problem of time dependent chromaticity in the Tevatron [3], early in these studies the chromaticities were rather large, causing a betatron tune spread which encompassed a number of betatron resonances. With practice it was possible to adjust the tunes and chromaticities during the reduction of the RF to avoid resonance overlap. This is an important consideration since particles whose tune overlapped a resonance were quickly ejected from the accelerator. Since chromaticity generated a correlation between betatron tune and momentum, these losses would generate gaps in the momentum distribution of the beam.

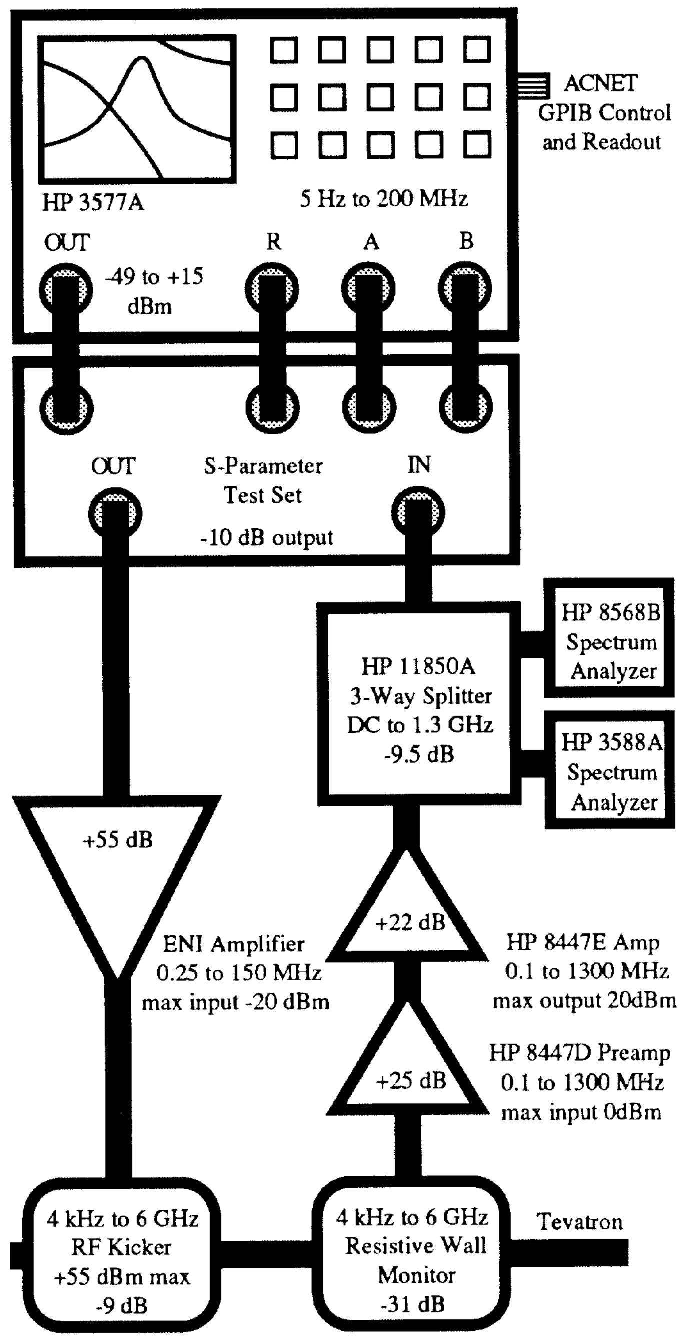

Figure 1: Schematic drawing of the experimental apparatus used to perform the longitudinal closed loop transfer function measurements.

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II. IMPEDANCE RESULTS

The first frequency band to be measured in the Tevatron was near the resonant frequency of the RF cavities at 53 MHz. There are 8 RF cavities, each having an unloaded shunt impedance of 1.2 MΩ and an unloaded Q of approximately 7100 [4]. With the cavities loaded to a Q of approximately 4000 [5], the total shunt impedance at harmonic h=1113 should be 5.4 MΩ. This is expected to be by far the largest single impedance in the Tevatron, and easily detectable.

The first measurements of the closed loop longitudinal transfer functions were quite unexpected. Instead of smooth amplitude and phase responses similar to those measured in the Fermilab Accumulator [6], the Tevatron beam responses contained deep notches and regions of remarkable structure. Figure 2 is an example of 6 superimposed response results from harmonic h=1100 to 1105. Using the resistive wall monitor as a longitudinal Schottky detector, and a Hewlett-Packard HP3588A dynamic signal analyzer centered at h=10, it was determined that the notches were actually in response to holes in the momentum distribution of the beam, as discussed earlier. This is a reasonable conclusion, since the structure is common to measurements at every harmonic.

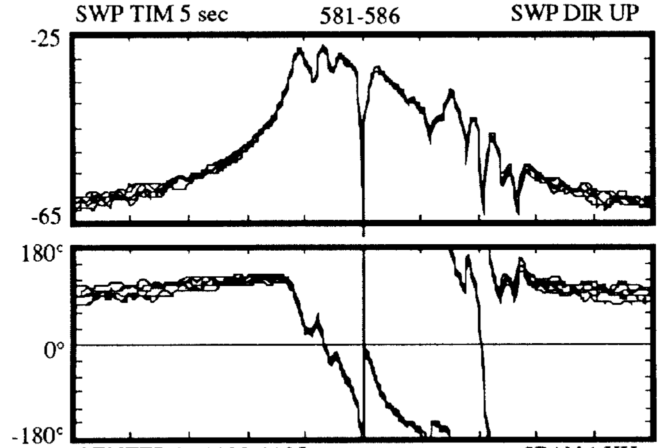

Figure 2: Superimposed results from closed loop longitudinal transfer function measurements at revolution frequency harmonics 1100 to 1105. The beam intensity was 4.3×10^{12}.

If one were to attempt to plot the inverse response from the data in figure 2 the result would be a series of apparently random curves traversing the complex impedance plane. After careful control of tunes and chromaticities, it is possible to get relatively clean inverse response curves, as shown in figure 3. In reality, since the determination of impedance is performed via calculations and not graphically, the existence of response structure is not an impediment to this method.

Analyzing the data from a set of inverse response measurements spanning the region around the RF frequency, from h=1100 to 1125, the real and imaginary parts of the longitudinal impedance can be calculated. The determination of the absolute shift in the inverse response requires knowledge of the momentum distribution, which was not measured. As a substitute for the preliminary analysis in this paper, revolution harmonic h=1100 was used as a reference (assumed to have zero longitudinal impedance). The data in figure 4 is the result of this analysis, where the estimated error is approximately 20%. Since the water temperature feedback system for the RF cavities was off, the cavity resonant frequencies were shifted away from h=1113. Therefore the nonzero imaginary impedance at h=1113 is reasonable, as is the smaller than expected real part of the impedance (1.4 MΩ).

In the future as time becomes available a systematic program of longitudinal impedance measurements will be pursued. The DC-200 MHz region will be studied first.

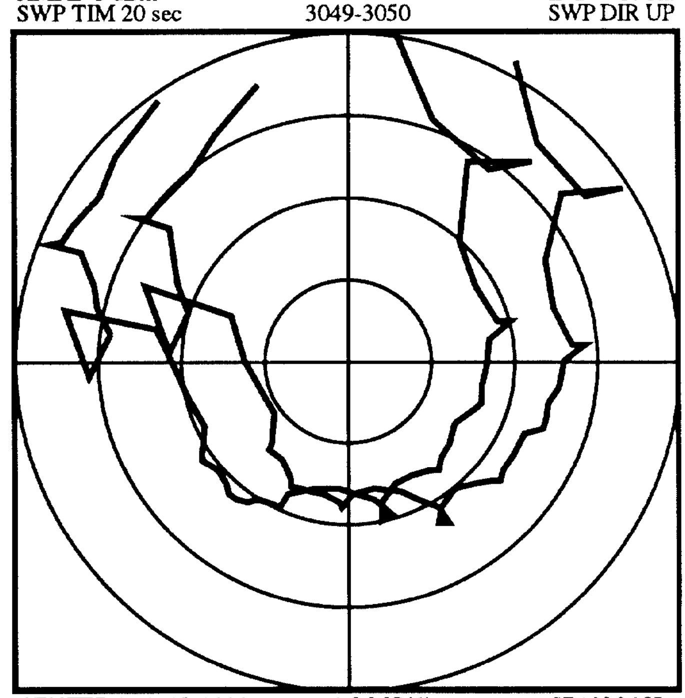

Figure 3: Inverse responses of the beam in the complex longitudinal impedance plane. The harmonics h=1113 and 1114 are plotted. The beam intensity was 5.0×10^{12}.

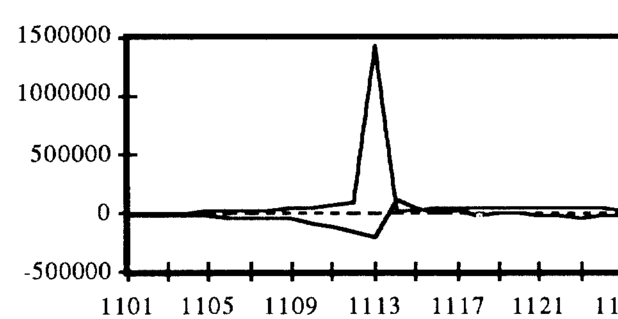

Figure 4: Measured real and imaginary part of the longitudinal impedance (Ω) as a function of revolution harmonic number in the region around the resonant frequency of the RF cavities.

III. OBSERVATION OF NONLINEAR PHENOMENA

Though the measurements of the impedance near the RF frequency show initial success, there are inconvenient and enigmatic phenomenon which have plagued these studies. In the inconvenient category is the impedance of the RF cavities. It is so high that often the coasting beam will spontaneously become self-bunching unstable. This has the effect of mixing the external modulation and the 53 MHz self-bunching modulation, therefore also sampling the impedance at their sum and difference frequencies. In addition, the momentum spread of the beam is increased until the instability disappears.

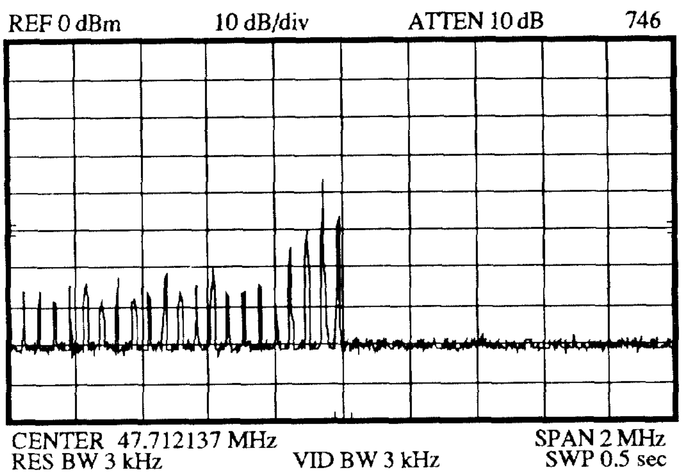

Figure 5: Observation of "ghost" lines during a transfer function measurement at h=1000 (rightmost peak). The spectrum analyzer was in max hold mode, and the beam intensity was 4.3×10^{12}.

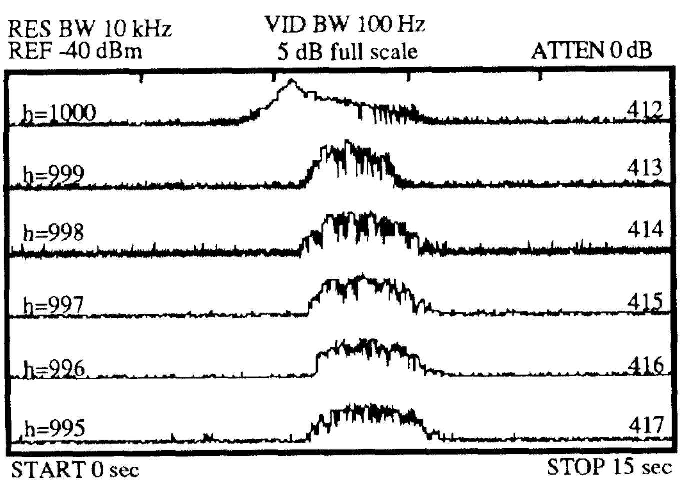

Figure 6: Power vs. time at each harmonic during a coincident longitudinal transfer function measurement at h=1000. The beam current was 10.8×10^{12}. The data was recorded measured by the HP8568B spectrum analyzer in zero span mode.

When the beam current was monitored over a broad frequency range while a transfer function measurement was in progress, it was noted that the revolution harmonic frequencies below the harmonic undergoing study were also excited. Figure 5 contains a typical example of this effect, which was captured by putting the spectrum analyzer in max hold mode. The time development of this phenomenon as a function of harmonic number is presented in figure 6. While studying this phenomenon these lines were dubbed "ghost" lines. When the speed of the network analyzer frequency sweep was drastically reduced, the effect disappeared. Figure 7 shows the resultant spectrum, which shows the residual AM modulation of the current due to mixing of the network analyzer drive and external electrical noise signals from a number of systems. In addition, below a threshold DC current (which depends on the momentum spread) the ghost lines no longer appear.

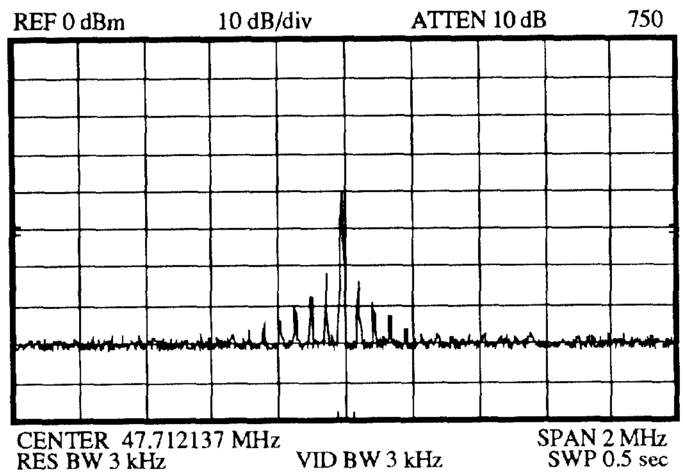

Figure 7: The exact conditions as presented in figure 5, except the transfer function sweep speed was reduced from 40 Hz/sec to 0.25 Hz/sec.

IV. REFERENCES

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