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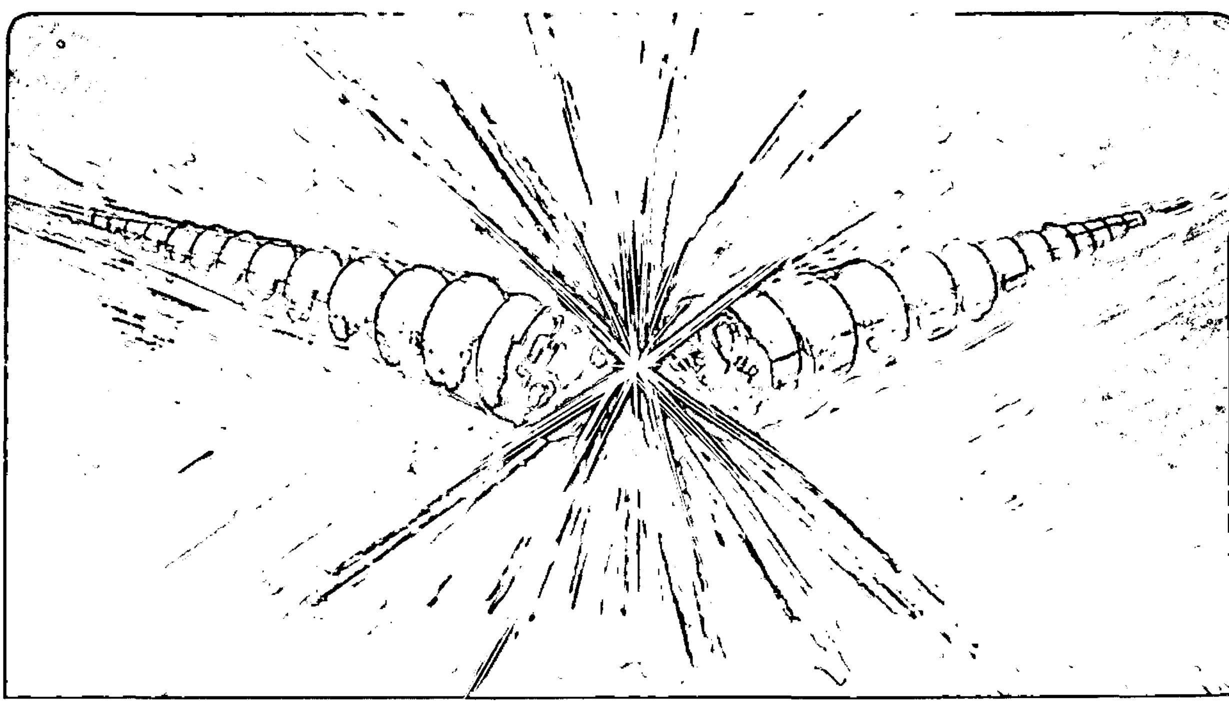

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SUCCESSFUL OBSERVATION OF SCHOTTKY SIGNALS AT THE TEVATRON COLLIDER*

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We have constructed a Schottky detector for the Tevatron collider in the form of a high-Q (≈5000) cavity[1] which operates at roughly 2 GHz, well above the frequency at which the Tevatron's single-bunch frequency spectrum begins to roll off. Initial spectra obtained from the detector show clearly observable Schottky betatron lines, free of coherent contaminants; also seen are the "common-mode" *longitudinal* signals due to the offset of the beam from the detector center. The latter signals indicate that at 2 GHz, the coherent single-bunch spectrum from the detector is reduced by > 80 dB; therefore, in normal collider operation, the Schottky betatron lines are >40 dB greater than their coherent counterparts. We describe how the data we have obtained give information on transverse and longitudinal emittances, synchrotron frequency, and betatron tunes, as well as reveal what may be previously unobserved phenomena. Space limitations restrict us to presenting only as much data as should be necessary to convince even the skeptical reader of the validity of the claim made in the paper's title.

INTRODUCTION

With the use of a suitable detector, one can sense fluctuations in the instantantaneous number and/or positions of particles in a cyclic accelerator. The nature of the signals from such detectors, the so-called Schottky signals, is described in detail in Ref. 1. Summarized briefly, the frequency spectrum of these signals consists of a set of bands occuring at integer multiples of the particle revolution frequency, and a second set which is shifted in frequency from the first set due to the particles' betatron motion; if the beam is bunched, the synchrotron motion splits these bands into a set of possibly overlapping satellite lines. One can use Schottky signals to obtain a variety of diagnostic information on a particle beam without perturbing it.[2]

A vexing problem associated with detection of Schottky signals from a bunched beam is the presence of the coherent signal, which can be 10 or more orders of magnitude greater than the Schottky signal. To overcome this difficulty, we have constructed a Schottky detector for the Tevatron collider, sensitive to *transverse* motion in both planes, in the form of a high-Q (≈5000) cavity[1] whose resonant frequencies (made slightly different for the vertical and horizontal sensing modes) are roughly 2 GHz, well above the frequency at which the coherent single-bunch frequency spectrum begins to roll off

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(≈200-300 MHz for the Tevatron). As described in Ref. 1, the signals are observed by heterodyning them down (in several stages) to frequencies within the 0-100 kHz range of a FFT signal analyzer, which makes it possible to obtain frequency resolution of ≈ 1 Hz (necessary for detailed observation of synchrotron satellite lines) in "reasonable" times. Since the revolution frequency of the Tevatron (and hence the Schottky band spacing) is roughly 48 kHz, this restricts one to viewing just over two Schottky bands at any one time; because of the peaked response of the detector, this does not constitute a significant added restriction.

EXPERIMENTAL RESULTS

Data were acquired during two separate Tevatron collider runs. The first of these was at 273 GeV which utilized the "fixed-target" optics, for which the vertical and horizontal beta functions at the detector location were approximately equal. The second run was at 900 GeV, and utilized the "low-β" optics, for which β_v is ≈ 8.5 β_h. A typical spectrum, obtained during the 273 GeV run, is shown in Figure 1, and illustrates most of the important features of the data (as explained in the Appendix, we "used" only the upper portion of the spectrum). We begin with an identification of these features, followed by detailed explanation which should also serve to justify the identification.

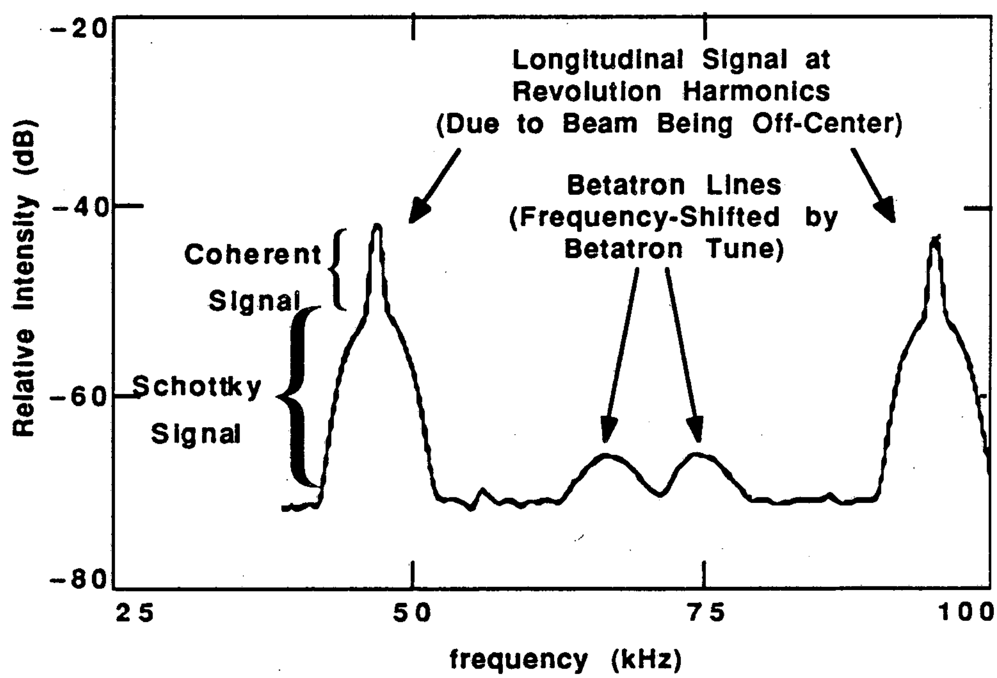

FIGURE 1 Spectrum of Vertical Output Signal from Schottky detector. E=273 GeV

The two large peaks at roughly 50 and 100 kHz are the longitudinal signals, variously known as revolution lines or (when they appear in a transverse detector which puts out a "difference" signal) common-mode lines. Their presence is due to the fact that the beam is not centered in the detector; in the spectrum coming directly from the detector (i.e., prior to heterodyning) they occur at integer multiples of the 47.7 kHz revolution frequency; both of the peaks in Fig. 1 are at frequencies corresponding to "weak" coherent lines (see Appendix). One notes that these are compound peaks–a narrow, intense peak atop a broad, weaker one. The strong, narrow peak is due to the residual coherent signal at 2 GHz; the broad peak is the longitudinal Schottky signal.

The two peaks appearing between the two revolution lines are the betatron signals. The line widths are comparable to those of the broad peaks seen in the revolution lines, and there is no evidence of the narrow peak, i.e. they appear to be Schottky signals completely uncontaminated by any coherent signal!

The breadth of the Schottky line reflects the momentum excursions of the individual particles within the beam, whereas that of the coherent line simply reflects the excursion of the *centroid* of the beam, which is considerably less. A graphical analysis of the width of the longitudinal Schottky peak (unlike the later 900 GeV run, data from this run were not stored digitally) is roughly 4.7 kHz which translates, for $\eta = .0028$, to a momentum width $\Delta p/p$ of roughly 8.3×10^{-4} (FWHM), slightly greater than the expected (undiluted) value of 6.8×10^{-4}; a perforce more precise analysis of the 900 GeV data gave a $\Delta p/p$ FWHM of 2.8×10^{-4}, a value indistinguishable from the expected one. Additional evidence for the identification of the two peaks was inadvertently supplied when the rf anode supply failed during one of the beam stores; the resulting debunching of the beam caused the coherent signal to disappear immediately, where as the the Schottky signal was (initially) unaffected.

To assess the effectiveness of operating at high frequency cavity to reduce the coherent signal, we make use of the expressions for the total power in the coherent and incoherent (Schottky) common mode lines.

$$P_c \propto \langle I_c^2 \rangle \cdot \langle x_d^2 \rangle \qquad\qquad P_S \propto \langle I_S^2 \rangle \cdot \langle x_d^2 \rangle \tag{1a,b}$$

Note that both signals are proportional to the mean-square beam displacement $< x^2{}_d>$. Hence the ratio of the mean-square Schottky and coherent currents is simply the ratio of the measured powers, i.e. of the areas under the respective peaks. For the data from the 273 GeV run, the ratio was obtained by assuming similar forms for the two line shapes, and comparing the products of amplitude and FWHM. For the 900 GeV method, it was also possible to numerically integrate the data as well. Comparisons of the two methods for the 900 GeV data gave answers which agreed to better than 1 dB. For the strong line (not shown) we obtained a ratio of coherent-to Schottky of $< 10^{3.5}$ with $\geq 5.5 \times 10^{11}$ particles in the beam, thereby indicating a reduction in the coherent signal of $> 10^8$ relative to its low-frequency value. For the weak lines (shown in Fig. 1), the ratio was reduced by an additional factor of 10^3 (30 dB).

An unexpected result, and one which is at present unexplained, is that the observed width of the coherent lines decreases by roughly a factor of 2 over the first few hours of a beam store (the width of the Schottky lines remains essentially unchanged during the same period) , accompanied by the appearance and disappearance of gross structure in the line shape; there does not appear to be any correlated change in the peak amplitudes of either the coherent or the Schottky signals. The above results for coherent line suppression are based on the measurements made in "steady-state," but would be only $\approx$3 dB different at the start of a store.

We can now estimate the degree to which the Schottky betatron lines are free of coherent contaminants. Expressions for the total power in the coherent and Schottky betatron peaks are given by

$$P_c^b \propto \langle I_c^2 \rangle \cdot \langle x_{\beta c}^2 \rangle \qquad\qquad P_S^b \propto \langle I_S^2 \rangle \cdot \langle x_{\beta i}^2 \rangle \qquad (2a,b)$$

where $< x^2{}_{\beta c} >$ and $< x^2{}_{\beta i} >$ are the mean-square coherent and incoherent betatron amplitudes, respectively. Hence in addition to the ratio of mean-square coherent to Schottky currents, the relative powers depend on the ratio $< x^2{}_{\beta c} > / < x^2{}_{\beta i} >$. We know from experiments done with the Tevatron tune detector that $< x^2{}_{\beta c} > / < x^2{}_{\beta i} > \leq 10^{-8}$, so that this additional suppression of 80 dB, means that the coherent contaminant in the betatron lines is some 45 dB below the Schottky signal (even for the case where the contaminant is produced by a *strong* coherent betatron line), a result consistent with its apparent total absence, as noted earlier.

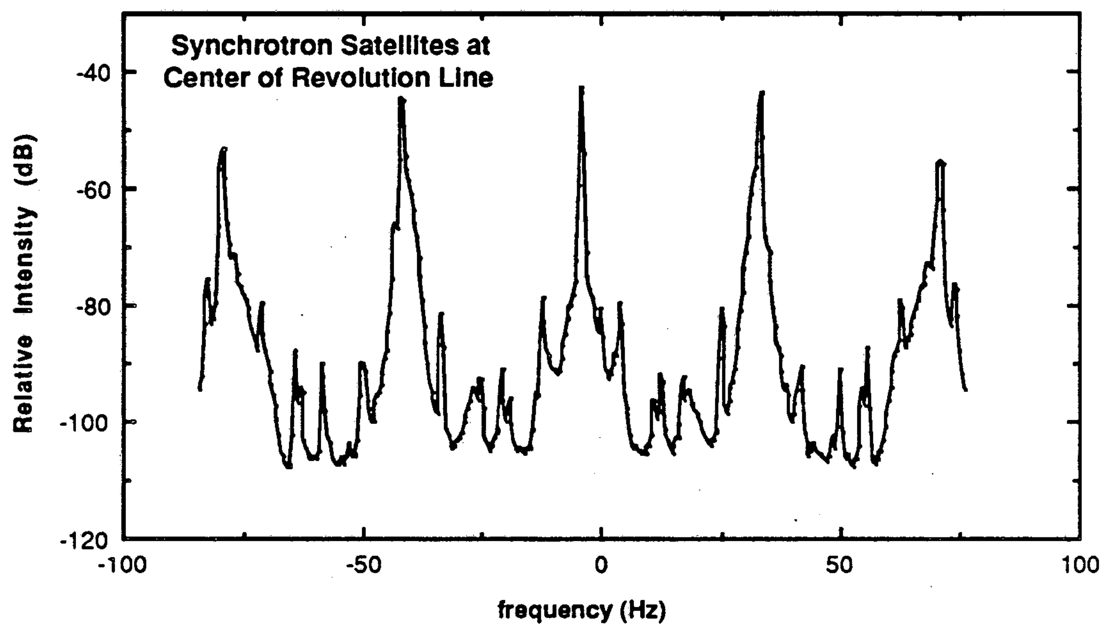

FIGURE 2 Central synchrotron satellites observed during opeation at ≈900 GeV.

The longitudinal lines in Fig. 1 are not in detail smooth curves but consist of a set of so-called synchrotron sidebands or satellites which result from the modulation of the particles' revolution frequency as a result of synchrotron oscillation. A greatly expanded view of the center of a revolution line (from the 900 GeV data) is shown in Fig. 2, which shows the central line (equivalent to the "carrier frequency") as well as the first two satellites on either side. The separation of the satellites is equal to the frequency at which the revolution frequency is modulated, i.e. the synchrotron frequency; from the data in Fig. 2 we determine that to be 37.6 ± 0.2 Hz[a]

[a] Strictly speaking, one should measure to the uppermost edge of the lines. The "shoulders" which begin about 25 dB down on the high-frequency side of the peak are not plausibly assignable to the peaks themselves; the initial drop in the high side of the peak is consistent with the instrument linewidth, an assertion borne out by the fact that the measured spacing of the first *four* satellites is constant to less than 0.1 Hz. By looking at increased peak width of the higher order satellites, we feel we can conservatively assert that the synchrotron frequency is at most .2 Hz greater than the measured satellite spacing.

We should note that the ability to obtain resolution of better than 1 Hz on signals which are originally at 2 GHz results from using the signal from the Tevatron rf system as the source of the heterodyning frequency. Nonetheless, the sharpness of the peaks indicates that the receiver has very low phase noise. (The central satellite, which is theoretically infinitely narrow, has a width consistent with instrument resolution when viewed at resolution bandwidth as low as .05 Hz!) Hence one is able to observe the considerable fine structure seen in Fig. 2. The fact that the structure is mirror-symmetric about the central satellite suggests that it is actually signal on the beam, and not either noise or an artifact of the heterodyning process. While the source(s) of the structure have not been identified, it is consistent with a group of particles within an annulus in the longitudinal phase space of the beam quite near to the outer edge of the rf bucket (not necessarily the same bucket as that containing the main portion of the beam); several individuals at Fermilab have independently suggested that such an annulus could be populated at the time the individual beam bunches are coalesced in the Main Ring.

One also expects to see satellite structure on the betatron peaks. When only protons are present we do indeed see them, with the same frequency spacing at which they are observed in the longitudinal spectrum. The lines (including the central peak) are much broader, about 11Hz FWHM. The most likely cause of this is the non-linear variation of the tune with betatron amplitude; the present technique appears to be a particularly convenient way of measuring this quantity. When $\bar{p}$'s are introduced along with the protons, the satellite structure disappears, presumably smeared out due to the beam-beam tune shift which, in addition to broadening the peaks, shifts those for p's and $\bar{p}$'s by different amounts. Were one to detect signals from p's and $\bar{p}$'s separately[1], it is possible that satellite structure could be recovered.

The final item for discussion is the betatron spectrum itself. The total power in the individual betatron lines, conveniently measured by viewing them with broad resolution, should provide a measure of the beam emittance. In the absence of an absolute calibration of the output signal level, we attempted normalization of the output signal level to the output noise level. Having previously measured the cavity characteristics[1] and the losses in the signal cable, we were able to calculate the effective signal-to-noise ratio (S/N) at the receiver input (including the 1 dB noise figure for the input amplifiers) as a function of beam size, using the values of the beam currents obtained from the Tevatron beam monitors, and the momentum width obtained from the Schottky monitor data. The output S/N was assumed to be degraded by 3 dB due to the lack of a filter in the first heterodyning stage. With roughly 5×10^{11} particles in the machine, we measured an output S/N for the vertical betatron signal of roughly 16 dB, which yielded a mean normalized emittance of roughly 20 π mm mrad, about 20% below the value obtained from the flying-wire data. An error of <1 dB in estimating the expected S/N would explain the observed discrepancy.

We should note that due to the asymmetry of the beta functions in the "low-β" mode, the above value of S/N is enhanced by roughly 3 dB over what it would be if one were using the more symmetric fixed-target optics (the obverse of that result is that the S/N for *horizontal* betatron line is degraded in this mode, having a S/N value of roughly 8 dB lower than that of the vertical signal for the same operating conditions). However, we are advised that a new set of "low-β" optics has been developed for the next collider run which has more nearly balanced beta functions, and should yield comfortable S/N ratios for signals from both planes.

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APPENDIX: A NOTE ON THE PERIODICITY OF THE SCHOTTKY SPECTRA

When the Tevatron collider is operated with three beam bunches (of p's and/or $\overline{\text{p}}$'s), one expects strong coherent lines at intervals of $3\,f_{rev}$; because of the non-uniform population of the individual bunches, weaker signals are also expected at the intermediate multiples of f_{rev}. With six bunches, the same situation obtains, because the operating rf harmonic (1113) is not an integer multiple of 6. The cavity is normally tuned[1] so that its peak responses (in both planes) lie midway between two of the $3\,f_{rev}$ lines; over that ≈150 kHz span the cavity's response is flat to ≈±0.3 dB.

Since the FFT analyzer can span 100 kHz, and the Schottky band spacing is only 47.7 kHz, the observed spectrum normally includes three revolution lines. However, due to an artifact of the final heterodyning stage, the lower half of the spectrum is generally distorted; consequently we analyzed only those data lying between (and including) the upper two revolution lines in any of the spectra. In the 273 GeV data, the final frequency conversion was normally done so as to make these both weak lines;for the 900 GeV runs the lower of the two was usually a strong line.

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