The Tevatron Resonant Schottky Detectors

Extracting the Proton and Antiproton Tunes

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INTRODUCTION

The following is a description of some studies I made on the resonant Schottky detectors in the Tevatron. I doubt that this document contains any information that wasn't known previously, but I hope that this document will serve as a useful self-contained reference for users of the system.

SYSTEM DESCRIPTION

There are two Schottky detector systems: one horizontal and one vertical. As is shown schematically in Fig. 1, each system consists of 2 identical detectors located 138 inches apart. The detectors are connected to a Schottky receiver that has two input channels: one for the upstream detector (here upstream and downstream refer to the proton direction) and one for the downstream detector. The receiver has two output channels: one for the proton Schottky spectrum and one for the antiproton spectrum. Some of the design features of detectors and the receivers have been published^{1,2} previously.

Fig. 1. Layout of a pair of resonant Schottky detectors.

DETECTOR RESONANT CIRCUIT

The resonant circuits can be modeled by an electrical circuit consisting of a parallel inductor and capacitor excited by a current source equal to the beam current. The detector resonant frequency is tuned by a variable capacitor controlled by a stepping motor. In order to obtain the maximum signal from the detectors the peak response (resonance) should occur at 21.4 MHz. A more critical requirement is the matching of the gain functions of the upstream and downstream detectors.

¹ D. Martin, et al., Particle Accelerator Conference, Chicago, IL, p 1486. (1989)

² D. Martin, et al., Particle Accelerator Conference, Chicago, IL, p 1483. (1989)

Fig. 2 shows the calculated response of the Schottky detector assuming a center frequency of 21.4 MHz and a Q of 370 (see reference 2). The response to proton and antiproton beams should be identical. The betatron sidebands are within a few kHz of 21.4 MHz resonance. The rapid rate of change of phase in the neighborhood of 21.4 MHz has important ramifications in matching the gain of the upstream and downstream detectors (see discussion below).

Fig. 2. Amplitude and phase response of the resonant Schottky detector. The amplitude response is in arbitrary units (dB).

PROTON AND ANTIPROTON SIGNAL SEPARATION: THEORY

The proton signal arrives at the upstream detector first and later arrives at the antiproton detector. Similarly the downstream detector sees the antiproton beam followed by the proton beam. The signals at the detectors can be written as

$$U(\omega) = g_U^p(\omega)p(\omega) + g_U^{\bar{p}}(\omega)\bar{p}(\omega)e^{-i\omega\tau} \quad [1]$$

and

$$D(\omega) = g_D^p(\omega)p(\omega)e^{-i\omega\tau} + g_D^{\bar{p}}(\omega)\bar{p}(\omega), \quad [2]$$

where $U(\omega)$ and $D(\omega)$ are the Fourier components of the upstream and downstream detector signals, $p(\omega)$ and $\bar{p}(\omega)$ are the Fourier components of the proton and antiproton signals in a unity gain detector, and τ is the transit time between detectors. The functions $g(\omega)$ describe the gain from each of the two detectors (upstream and downstream) through each of the two outputs (proton and antiproton). The gain function describes variations in detector construction and electronic response functions of nominally identical channels.

Eqns. [1] and [2] can be solved to separate the detected signals into the proton and antiproton components. The result is

$$p(\omega) = \frac{g_D^{\bar{p}}(\omega)U(\omega)e^{i\omega\tau} - g_U^{\bar{p}}(\omega)D(\omega)}{g_U^p(\omega)g_D^{\bar{p}}(\omega)e^{i\omega\tau} - g_D^p(\omega)g_U^{\bar{p}}(\omega)e^{-i\omega\tau}} \quad [3]$$

and

$$\bar{p}(\omega) = \frac{g_U^p(\omega)D(\omega)e^{i\omega\tau} - g_D^p(\omega)U(\omega)}{g_U^p(\omega)g_D^{\bar{p}}(\omega)e^{i\omega\tau} - g_D^p(\omega)g_U^{\bar{p}}(\omega)e^{-i\omega\tau}}. \quad [4]$$

Eqns. [3] and [4] are unwieldy to implement with analog electronics. However, for the frequency ω_r , where $\sin \omega_r \tau = 1$, Eqns. [3] and [4] may be simplified to

$$p(\omega_r) = \frac{i}{2g_p} [U(\omega_r) - iD(\omega_r)] \quad [5]$$

$$\bar{p}(\omega_r) = \frac{1}{2g_{\bar{p}}} [U(\omega_r) + iD(\omega_r)] \quad [6]$$

provided that the gains are equalized, viz.,

$$g_U^p(\omega_r) = g_D^p(\omega_r) \quad [7]$$

and

$$g_U^{\bar{p}}(\omega_r) = g_D^{\bar{p}}(\omega_r). \quad [8]$$

Conditions [7] and [8] can be achieved by tuning an appropriate gain and phase adjustment and Eqns. [5] and [6] can be implemented in the analog hardware using quadrature hybrids. The detectors and Schottky receivers are constructed to resonate at the frequency $f_r = \omega_r/2\pi$. Provided that the gain functions vary slowly, Eqns. [5] and [6] will be approximately valid in the neighborhood of ω_r .

The frequency $f_r = 21.4$ MHz was chosen primarily because excellent crystal filters are economically available at that frequency. The required transit time between detectors is

$$\begin{aligned}
\tau &= \frac{1}{4f_r} \\
&= \frac{1}{4 \cdot 21.4 \times 10^6} \text{ sec} \\
&= 11.68 \text{ nsec}
\end{aligned} \tag{9}$$

and the detector spacing ℓ is

$$\begin{aligned}
\ell &= c\tau \\
&= 2.998 \times 10^8 \cdot 11.68 \times 10^{-9} \\
&= 3.502 \text{ m} \\
&= 137.9 \text{ in}
\end{aligned} \tag{10}$$

GAIN MATCHING

The ability to separate proton and antiproton signals is limited almost exclusively by the inability to exactly maintain the gain matching (Eqns. [7] and [8]) over the entire Schottky band. Differential adjustments to the amplitude and phase of the gain make it possible to achieve equality of the gains at any single frequency. Roughly speaking, the gain and phase adjustments in the Schottky receivers effectively rescale the gain functions by a complex constant k as follows:

$$g'_U(\omega) = k g_U(\omega) \tag{11}$$

$$g'_D(\omega) = \frac{1}{k} g_D(\omega)$$

$$g'_U(\omega) = k g_U(\omega) \tag{12}$$

$$g'_D(\omega) = \frac{1}{k} g_D(\omega)$$

In practice, the gain applied to the upstream leg is not equal to the attenuation applied to the downstream leg. This inequality is the result of using attenuators whose attenuation is not proportional to the control voltage.

It is easy to calculate how accurately the gain functions must be matched in order to get a given degree of cancellation. Assume that the unprimed quantities in Eqns. [11] and [12] are exactly equal, but that because of tuning errors the signals corresponding to the primed gains are processed by the Schottky receiver. The antiproton output will consist of the antiproton signal (proportional to $k + 1/k$) and the proton signal (proportional to $k - 1/k$). The suppression factor is defined to be:

$$S = \left| \frac{k^2 - 1}{k^2 + 1} \right| \tag{13}$$

The suppression factor is plotted in Fig. 3 versus phase and amplitude errors. A suppression factor of 20 dB requires amplitude matching of about 0.5 dB and phase matching of about 2° . ²⁵

Fig. 3. The suppression factor. Contours at -10, -15, -20, and -25 dB.

The amplitude and phase adjustment in the Schottky detectors is nominally ± 20 dB and $\pm 10^\circ$. The actual amplitude adjustment is more like +3 dB on one leg and -15 dB on the other, but the range is adequate in practice. However, small errors in tuning the detector can easily cause phase shifts outside the $\pm 10^\circ$ tuning range. Fig. 4 shows the error in amplitude versus the error in phase that comes from a tuning error. If the detectors are tuned based on amplitude, the peak must be carefully determined (to within a fraction of a dB) in order to avoid unwanted phase errors. The procedure for detector tuning is given in Appendix I.

Fig. 4. Detector tuning amplitude loss versus phase error.

GAIN MEASUREMENT VERSUS AMPLITUDE

The gain of the Schottky receivers was measured with the gain balance set to its nominal (0 dB) value. A sine wave signal of known amplitude was applied to either the upstream or downstream input and the output amplitude was measured for both the proton and antiproton outputs. The input amplitude was varied in steps of 10 dB and the output amplitude was measured on a spectrum analyzer. The input amplitude was determined by the settings on the frequency source. The amplitude settings were checked with the spectrum analyzer and found to agree to better than 1 dB (except at very small signal levels where the noise floor distorts the measurement). The data for this check is shown in Fig 5. The results of the gain measurements are shown in Fig. 6. The line drawn on the graphs is a slope=1 line with a offset determined by a fit to the data. This offset is the gain given on the lower right hand corner of the graphs.

Fig. 5. Input power setting versus measured input power.

Fig. 6. Gain (amplitude only) measurements of the horizontal and vertical Schottky detectors.

NOISE MEASUREMENT

The noise spectrum was measured for each output on each receiver. The measurements were made with the inputs terminated in $50\ \Omega$ and the differential attenuator and phase shift set to their nominal (0) values. The results of these measurements are shown in Fig. 7.

The noise measurements in shown in Fig. 7, and the gain measurements in Fig. 6 can be combined to obtain the noise figure of the receiver. The noise figure measurements are summarized in Table I. The measured noise figure of 10 dB is considerably larger than the published value of 1.8 dB. The source of the discrepancy is not understood. The method in this paper is somewhat crude and does depend having the correct bandwidth and amplitude calibration in the spectrum analyzer. Nonetheless, it is difficult to reconcile a difference of 8 dB in noise figure measurements.

Table I. Estimated noise figure of the receivers.

Receiver Output	Noise Level (dbm/30 Hz)	Gain (dB)	Noise Figure (dB)
H Proton	-56	92.6	10.5
H Pbar	-57	91.5	10.6
V Proton	-57	91.7	10.3
V Pbar	-57	88.7	13.4

Fig. 7. Noise spectrum measurements of Schottky receiver outputs: horizontal proton (a), horizontal antiproton (b), vertical proton (c), and vertical antiproton (d).

GAIN MEASUREMENT VERSUS FREQUENCY

The small signal gain of the Schottky receivers was measured at small signal levels using a network analyzer. The transfer function was measured from each input to each output for each receiver. The results of these measurements is shown in Fig. 8 (horizontal receiver) and Fig. 9 (vertical receiver).

One can also measure rather directly the cancellation possible with these receivers. The measurement is made by splitting the network analyzer output and delaying either the upstream or downstream leg by one quarter wavelength (11.68 nsec). The attenuation and phase adjustments are optimized (by eye) to achieve good cancellation of the undesired signal at about 27 kHz. The results of these measurements are shown in Fig. 10. Comparison of Fig. 10 with Figs. 8 and 9 indicates that one should typically be able to achieve 20-30 dB suppression of the unwanted signal with these receivers.

SUPPRESSION OF THE UNWANTED SIGNAL: BEAM MEASUREMENTS

It is easy to measure the rejection of the proton signal in the antiproton output when only protons are stored in the Tevatron. Figure 11 illustrates the suppression of the unwanted proton signal in the antiproton output. The cancellation shows some sensitivity to beam position. This sensitivity is not understood in detail, but might be explained by variations in detector sensitivity with beam position.

CONCLUSION:

The resonant Schottky system used in the Tevatron has been described theoretically and has been subjected to some experimental tests. The system generally behaves as expected. A clear weakness of the system lies in the necessity of precisely tuning the gain and phase of the upstream and downstream detectors in order to separate proton and antiproton tunes.

Fig. 8. Horizontal Schottky receiver gain functions. Shown are proton upstream (a), proton downstream (b), antiproton upstream (c), and antiproton downstream (d).

Fig. 9. Vertical Schottky receiver gain functions. Shown are proton upstream (a), proton downstream (b), antiproton upstream (c), and antiproton downstream (d).

Fig. 10. Schottky receiver gain for the undesired signal combination after tuning to minimize the signal. Shown are horizontal proton (a), horizontal antiproton (b), vertical proton (c), and vertical antiproton (d).

Fig. 11. Suppression of the unwanted proton signal on the antiproton output using a proton-only beam at 150 GeV. The pictures are a) proton output, b) antiproton output with beam displaced +5 mm at the schottky detectors, and d) antiproton output with beam displaced -5 mm at the Schottky detectors.

Appendix

Procedure for Tuning Tevatron Resonant Schottky Detectors

1. DETECTOR RESONANT FREQUENCY

Each detector has an individual capacitor that can be varied to change its resonant frequency. The capacitor should be tuned so that the resonant frequency is approximately 21.4 MHz. More precisely the resonant frequency should be tuned to harmonic number 448.5, *i.e.*, half-way between harmonic number 448 and 449. Follow this procedure for each of the four resonant pickups.

1. Inject and store a single coalesced proton bunch at 150 GeV. The reason for having a single coalesced bunch is that it will produce equal intensity lines at each revolution harmonic. The energy is unimportant, but 150 GeV is probably most convenient. The separator state shouldn't matter, but leave them off. The satellite intensity is not crucial, but small satellites are desirable.
2. Unplug the desired detector from the Schottky receiver input and plug it in to a spectrum analyzer tuned to 21.4 MHz with a span of 100 kHz. The revolution lines at harmonic 448 and 449 should be plainly visible.
3. Set up the spectrum analyzer to get a good measurement of the relative heights of the revolution lines. The main ring ramp causes fluctuations of 1 dB or more in height. Good measurements can be obtained by digital averaging 100 traces.
4. Enter C36.
5. Select the desired detector.
6. Select manual
7. Select "GO TO STOP" under digital status.
8. Manually increase the counts until the resonance condition is achieved. If the stepping motor is advanced beyond the resonance condition, retreat to step 7 and try again. The resonance condition should also be obtained only by increasing the step counter. This method minimizes the irreproducible results that would otherwise result from the mechanical backlash.

The resonance condition is achieved when the two revolution lines have equal amplitude. Typically at the STOP the two revolution lines will be 2 or 3 dB different in amplitude. As the counter is increased, both lines will increase, but the difference in amplitude will be approximately constant. As resonance is approached, the difference in amplitude will increase to about 6 dB and then decrease to zero. The resonance condition is achieved when the amplitude difference is within 0.3 dB. An example of the spectra obtained before and after tuning is shown in Fig. A1.

Fig. A1. Tuning the Horizontal Upstream detector. The as found state (a) and the state after tuning (b) are shown. After tuning, the two revolution harmonics have equal amplitudes.

2. NULLING THE PROTON SIGNAL AT THE ANTIPROTON OUTPUT

The signal nulling can be performed in a "scientific" fashion by exciting the beam and by comparing the phase and amplitude response of the upstream and downstream detectors. In practice, I have found it easier to tune the detectors by tuning (essentially a gradient search to find the minimum).

1. Make sure that the detectors have been tuned recently (see procedure above). I don't have a precise definition of "recently." However, if you are unable to obtain a clear minimum in the signal either the detectors, it is likely that they are out of tune.
2. Inject 6 coalesced proton bunches at 150 GeV with the separators off. The number of bunches or whether they are coalesced shouldn't matter, the state of the separators makes a slight difference.
3. Observe the output of the Horizontal antiproton Schottky receiver on a spectrum analyzer (in the control room is adequate). Use the amplitude and phase trim adjustments to obtain a minimum signal. The ACNET names of these devices are given in Table A1.
4. The amplitude adjustment increases the amplitude of the upstream detector and decreases the amplitude of the downstream detector. Adjust the amplitude vernier until the signal is minimized. Fig. A2 shows theoretically how the signal amplitude would behave as an ideal amplitude adjustment is tuned under the assumption of a 10° phase error. . However, the attenuator is not ideal and the actual tuning curve is substantially flatter than Fig. A2 at large magnitude tuning error. The maximum signal increase is 2-3 dB while the attenuation can be 10 dB or more. Despite these difficulties, a clear minimum should be seen provided the phase error is 10° or less.
4. The phase adjustment increases the phase of the upstream detector and decreases the phase of the downstream detector. The range of the phase adjustment is only $\pm 10^\circ$. It is crucial that the upstream and downstream resonant pickups be properly tuned in order to obtain satisfactory results. Adjust the phase until the signal is minimized.
5. Repeat steps 3 and 4 until no further reduction of the signal is possible.

Table A1. ACNET names of the differential amplitude and phase controls.

ACNET Name	Controls
T:SA17H0	H Proton Differential Gain
T:SA17H1	H Proton Differential Phase
T:SA17H2	H Pbar Differential Gain
T:SA17H3	H Pbar Differential Phase
T:SA17V0	V Proton Differential Gain
T:SA17V1	V Proton Differential Phase
T:SA17V2	V Pbar Differential Gain
T:SA17V3	V Pbar Differential Phase

In principle, one could load the Tevatron with antiprotons and null the proton circuit, but this opportunity exists rarely, if at all. A more realistic procedure is to identify the antiproton tunes on the proton output with colliding beams and to minimize the antiproton signals in the presence of the proton beam.

Fig. A2. Signal size versus amplitude tuning error for a 10 degree phase error.