

A SCHOTTKY RECEIVER FOR NON-PERTURBATIVE TUNE MONITORING IN THE TEVATRON

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Abstract

Transverse Schottky noise and coherent betatron modulation of the bunched beam revolution harmonics are continuously monitored by a sensitive receiver. The electronics relies upon low noise amplifiers, narrow-band filters, and spectrally pure oscillators to obtain a minimum detectable signal of -160 dBm. Dynamic range is 80 dB. Separate baseband proton and antiproton signals are continuously analyzed in the Main Control Room.

Introduction

Beam signals from the resonant Schottky detectors¹ are amplified, filtered and processed by a Schottky receiver. (Fig. 1). An early single channel receiver (Fig. 2) processed signals from a single detector. This electronics filtered the 21.4 MHz signals with a narrowband (15 kHz) 2-pole crystal BPF, offering 22 dB rejection of nearby revolution lines. The tune signals were subsequently filtered with sharper filters. A double conversion mixer scheme converted the signals to baseband. The system presently in operation in the Tevatron collider is a prototype "directional" receiver, and is the principal subject of this discussion. Since the directional receiver shares design concepts with the earlier one, analysis of it should cover its forebears.

The Schottky receiver is a low noise, high gain, fixed frequency detection system. The task of the receiver is to incorruptibly extract information (amplitude and frequency) from the input signals and present them in a perceptible form. The specifications we wished to attain were:

Schottky Receiver Specifications

1. ~90 dB Gain @ 21.400 MHz
2. < 1 dB Noise Figure
3. 15 kHz Bandwidth ($.35 < q < .65$)
4. Accurate Freq. Translation to Baseband
5. Frequency Normalization of Deterministic Freq. Change
6. Low I.M. Distortion
7. > 145 dB Shielding

Receiver Design

Signals enter the receiver through noise reduction chokes, which are electrically external to the receiver. The cable jackets from the detectors are rich with power line, SCR and RF noise. Lossy ferrite cores lower the EMF that would otherwise appear at the receiver input. To obtain a low noise figure, gain in the first stage is essential. This gain overcomes signal losses in the quadrature sum and difference circuit. Saturation by revolution line power is also a concern, so filtering early in the receiver is necessary. We therefore combined filtering and gain in the first stage with a helically tuned amplifier. The amplifier bandwidth (120 kHz) is small enough to reduce the total parasitic signal power while not posing extraordinary drift and matching problems. The input amplifier is represented schematically in Fig. 3. The transistor is a low noise, small signal, high gain type, MRF 572. Because S-parameter data was not available at 21.4 MHz, the parameters were measured. $S_{11} = .715 \angle -21$, $S_{12} = .008 \angle -83$, $S_{21} = 35.3 \angle 188$, $S_{22} = .943 \angle -11$ @ $V_{CE} = 6V$ and $I_C = 15 mA$. The stability factor² k is given by:

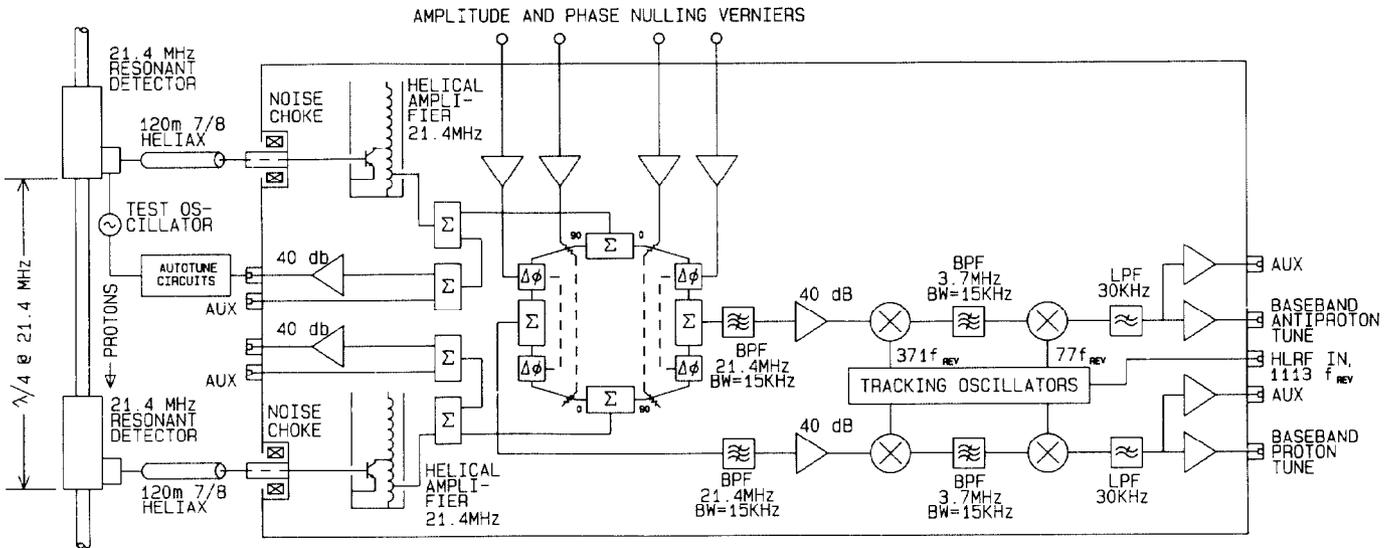


Fig. 1 Schottky Low Noise Receiver-Block Diagram

*Operated by Universities Research Association under contract with United States Department of Energy

$$k = \frac{1 + |S_{11}S_{22} - S_{12}S_{21}| - |S_{11}|^2 - |S_{22}|^2}{2 |S_{12}| |S_{21}|} \quad (1)$$

Since $k = -0.13$, a simultaneous input/output match would be unstable. The input match was therefore optimized for noise figure ($\Gamma_{NF} = 0.43457 @ 500 \text{ MHz}$), and the output match for 50Ω . This limits the input return loss to about 12 dB, while the output loss, if carefully adjusted, is 40 dB or more. A surreptitious advantage to the lumped element matching networks is suppression of the higher order helix resonances.

The collector of the transistor drives the $\lambda/4$ resonator at the tap point ($\sim 1.5 K\Omega$) that provides maximum power transfer to the 50Ω load. The transistor emitter is partially degenerated to set and stabilize the gain at 20 dB, making the NF slightly worse. The power and ground connections are inverted to avoid using a blocking capacitor at the shorted end of the resonator. The measured NF of the amplifier is 1.8 dB; power output is +7 dBm @ 1 dB GCP. Because the amplifiers are used in matched pairs, each unit is burned-in at 70°C for 24 hrs. prior to final alignment.

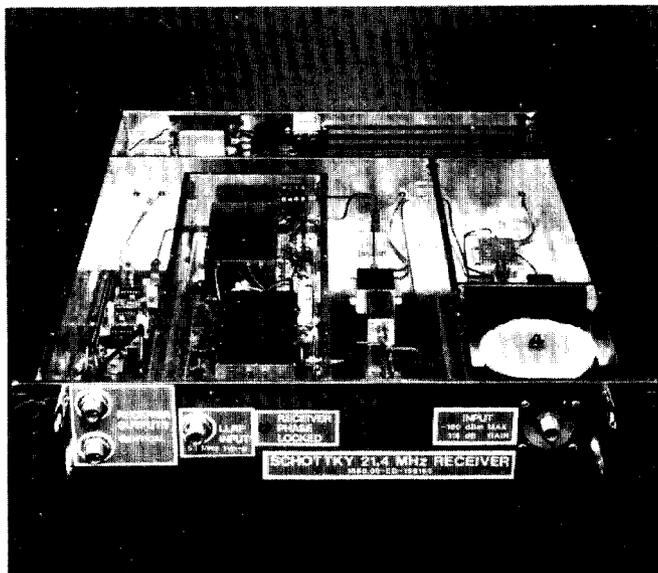


Figure 2.

Phase quadrature circuits allow proton and antiproton tunes to be resolved from the composite detector signals. For example, the antiproton signals from the two detectors combine with 3 dB gain, while the proton signals at the same port are cancelled, one proton signal phase retarded by 180° . As the two beam detectors are slightly different in Q , sensitivity, center frequency, etc., amplitude and phase verniers are needed to achieve cancellation. In operation this circuit has reduced proton tunes to the system noise floor leaving an antiproton tune spectrum only. Bench tests show the circuit is capable of 70 dB rejection.

The receiver uses double frequency conversion to obtain image rejection. If a single mixer were used, the betatron sideband near $447.5f_0$ would produce a baseband signal indistinguishable from $448.5f_0$. The mixers are fed by synthesizing VCXO's which derive their frequency from the 53 MHz LLRF. Crystal oscillators were chosen for their low phase noise and narrow tuning range. The first stage VCXO frequency is

$371f_0$; the second stage $77f_0$. The frequency coefficients are obtained using ECL 10136 counters and 12040 phase/frequency detectors in PLL configurations. A "phase-locked" indicator alerts personnel that both synthesizers are functioning.

We were concerned about deterministic modulation of the oscillators, since any modulation here could appear in the tune spectrum. To avoid this, the frequency control line to each VCXO was heavily filtered, the bandwidth established by the maximum Tevatron $d\text{fpp}/dt$. We recognized that some of the modulation observed on the beam would be produced by the RF system, but decided that clean, filtered oscillators would simplify the interpretation of beam data. Each oscillator is doubly shielded, since they must coexist with the noisy logic circuits.

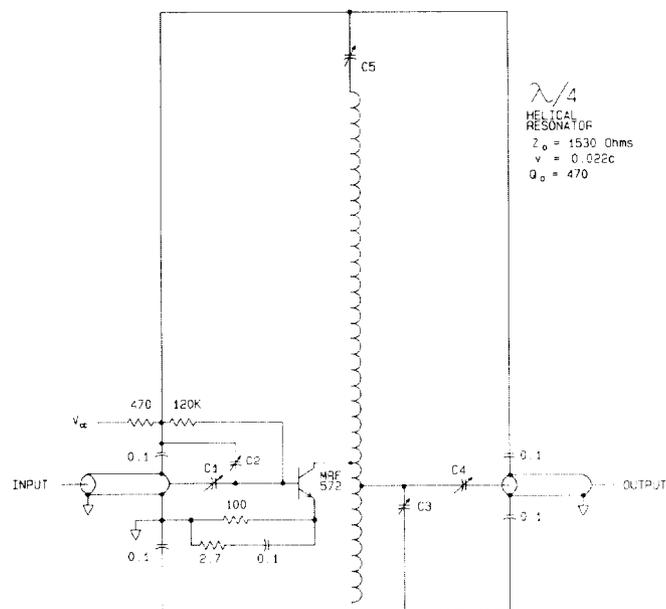


FIG. 3 SCHOTTKY RECEIVER TUNED AMPLIFIER

Tune signals at baseband are amplified, filtered and split using low noise op-amps. In the early design, a high order active elliptic filter was used to obtain revolution line suppression. A less ambitious filter is now used because of the elliptic filter noise contribution. The baseband signals are transmitted to MCR over RG-8 cables at levels up to 20 Vpp, and are attenuated before the 100 kHz FFT analyzer. This approach to suppressing cable pickup is brute force, but has worked well, with the minor advantage of placing all RF signal processing in a single chassis.

The receiver chassis is constructed of 1/4 in. thick aluminum plate, welded together with internal bulkheads and compartments. This framework is plated with 1/2 mil tin to improve contact between bolted joints. The heavy material was chosen to tolerate welding and to accommodate numerous threaded holes. Critical signal devices are interconnected by .141 in. semirigid line, which passes through bulkheads unbroken, but grounded. One compartment is taken by power supplies and line filters, which suppress noise above 1 MHz or so. For noise below 1 MHz, a rack mounted line filter was constructed. Consisting of a doubly shielded isolation transformer and Pi filters, the filter cutoff is 700 Hz. All Schottky receivers and peripheral RF processing electronics are installed

in an electrically sealed relay rack. Except for the balun terminated signal cables, no ungrounded, unshielded conductors are allowed to enter the rack. These measures were taken as precautions, but proved to be not entirely adequate: Occasional phantom signals appeared in MCR. The interference was linked to amateur radio operation and an interfering signal of -148 dBm was measured. Since this signal is 13 dB over MDS, it appeared strong on the MCR analyzer. The problem was eliminated by a redoubled design of the input noise choke.

Beam Observations

This system is used extensively during both normal colliding beam operations and during specialized Tevatron accelerator studies. Two Hewlett-Packard HP3561A Dynamic Signal Analyzers have been installed in the Tevatron control room, one looking at the horizontal plane and the other looking at either the proton or antiproton signal in the vertical plane.

A typical example of observed spectra is shown in Fig 4. The vertical scale is rms voltage in dbV, the horizontal scale is in units of tune, called ords. There are 400 bins per spectrum, so a span of 0.0524 ords yields a bandwidth of 0.000131, or 6.25 Hz. The top spectrum is from the horizontal plate, the bottom is the vertical proton signal. The horizontal and vertical receiver gains are not the same. Due to coupling, two betatron normal modes appear on each plate.

The Johnson noise level is 5 dB below the noise baseline in Fig. 4., vertical plane, indicating a higher noise figure than is measured at the test bench (2 dB). Revolution line power, in effect, raises the NF of the receiver, a problem we hope to solve with the new equipment. Despite the degradation, Schottky noise signals have been observed in the Tevatron when the beam is debunched.

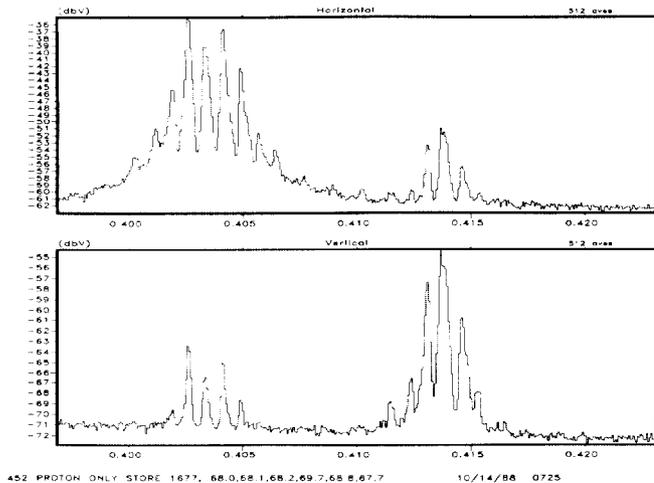


Figure 4.

During normal colliding beam operations the plates are maintained approximately 25 mm apart, even though the rms width of the beam at the maximum Tevatron energy of 900 GeV is approximately 0.7 mm. The reasons for this large gap are both injection aperture and the lack of adequate closed orbit control when the Tevatron energy is ramped. As a result, the signal to noise ratio is smaller than optimum.

Even so, it is evident that there is sufficient signal to noise for tune measurements with only minimal spectral averaging. Coherent motion equivalent to 6-10 dB above Schottky noise is typical. The reason is that the signal is dominantly the beam response to external power supply noise. When the power supply noise induced transverse deflections have spectral power at any of the betatron sidebands, the beam responds and the power in the observed betatron lines increases. Several candidate supplies have been identified, and a program of modifications is underway to remove the noise.

Future Developments

In receiver design an adage states, "Gain is cheap, selectivity is expensive", and our experience did not refute this common wisdom. The operating frequency placed at our disposal a variety of crystal filters of various bandwidths, shape factors and package styles. We soon found that nonlinear effects in the filters (noise and tone production in the passband when excited by strong stopband signals) were a serious problem. Our measurement of this effect at $n=448$ gave an approximately linear relationship between passband and stopband power: $P_{pb} = P_{sb} - 60$ dB, valid to about $P_{sb} = -60$ dBm. Below this level, high oscillator phase noise made the measurement imprecise. Testing several varieties of filters for this effect showed filter shape factor not to be an important variable. For this reason, we retained the sharper, higher insertion loss filters, putting them at later points in the cascade.

Under some operational conditions, large revolution harmonics (-20 dBm/line) have obscured the tune signals. This problem has not been entirely resolved. Nonetheless, crystal filters remain the filter of choice under most circumstances for high Q, small size and simplicity.

A plan is now afoot to run separated proton and antiproton orbits in the Tevatron. This mode has two consequences to tune monitoring. First, freedom to center pickup electrodes on the beam will be lost or restricted, so revolution line power at the receiver will increase. Under consideration is a passive, narrowband ($Q_0 \sim 5000$) helical trap placed before the receiver. The reflective attenuation at $n=448,449$ would be 15 dB. The unit temperature could be used as a frequency vernier in a feedback loop.

With larger sideband power will come lower sensitivity and smaller signals. Recently a preliminary design for a varactor diode parametric amplifier has been completed. Using a pump frequency of 5.1 GHz, and pump power ~ 0.5 W, a very low noise figure ($F = .05$ dB) amplifier should be achieved.

References

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- [3] G. Jackson, Tune Spectra in the Tevatron Collider, this Proceedings.