REVIEW OF MICROWAVE SCHOTTKY BEAM DIAGNOSTICS *

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Abstract

A means for non-invasive measurement of transverse and longitudinal characteristics of bunched beams in synchrotrons has been developed based on high sensitivity slotted waveguide pickups. The pickups allow for bandwidths exceeding hundreds of MHz while maintaining good beam sensitivity characteristics. Wide bandwidth is essential to allow bunch-by-bunch measurements by means of a fast gate. The Schottky detector system is installed and successfully commissioned in the Fermilab Tevatron, Recycler and CERN LHC synchrotrons. Measurement capabilities include tune, chromaticity, and momentum spread of single or multiple beam bunches in any combination. With appropriate calibrations, emittance can also be measured by integrating the area under the incoherent tune sidebands.

INTRODUCTION

The Schottky detector is based on the stochastic cooling pickups [1] that were developed for the Fermilab Antiproton Source Debuncher cooling upgrade, which was completed in 2002. These slotted line waveguide pickups have the advantage of large aperture coupled with high beam coupling characteristics. For stochastic cooling, wide bandwidths are integral to cooling performance. The bandwidth of slotted waveguide pickups can be tailored by choosing the length of the pickup and slot spacing. For use as a Schottky detector, bandwidths of 100-200 MHz are required for gating, resulting in higher transfer impedance than those used for stochastic cooling.

Bunched beam stochastic cooling was attempted in the Tevatron [2] in the mid 1990s but was unsuccessful due to the large coherent signals produced by the bunched beams. Observance of the Schottky signals at microwave frequencies revealed incoherent as well as coherent frequency bands containing relevant transverse and longitudinal characteristics of the beam. Depending on the bunch fill pattern, the coherent signals fluctuate significantly from revolution line to line, but due to the broadband nature of the system, a high instantaneous dynamic range is required to maintain linear performance, Figure 1.

Many diagnostic systems for the measurement of beam parameters utilize resonant circuits to increase beam sensitivity. Such resonant characteristics do not allow the investigation of individual beam bunches spaced by tens of nanoseconds due to the ringing that results from the higher Quality factor (Q). If a diagnostic system could be made wide band so that gating would enable the extraction of bunch-by-bunch data and retain adequate signal to noise ratio, an investigation of individual or multiple bunch characteristics could be explored.

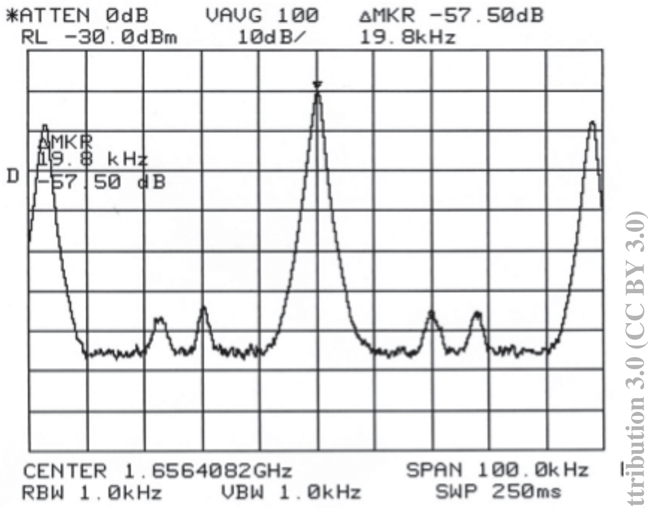

Figure 1: Tevatron Schottky spectrum.

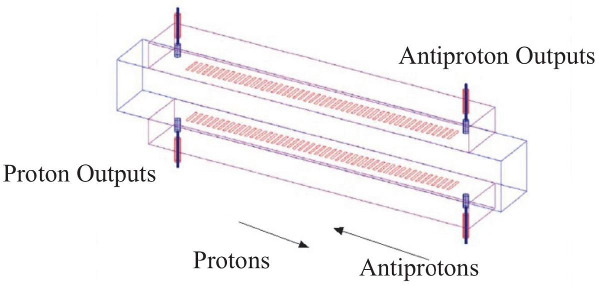

Figure 2: Model of slotted waveguide structure.

In 2003 after the completion of the Debuncher stochastic cooling project, a Schottky diagnostic system for the Fermilab Tevatron and Recycler was proposed and implemented [3]. The center frequency chosen was 1.7 GHz based on the required minimum beam aperture of the pickup (70mm x 70 mm) and the availability of surplus microwave hardware from the recently decommissioned 1-2 GHz Stacktail cooling system in the Accumulator. With successful operating systems at Fermilab [4,5], it was suggested that a similar system would be beneficial to the CERN LHC, which was under construction at the time. In 2004, a proposal was made to the LARP [6] collaboration that such a system be developed under their auspices. The LHC system would be centered at 4.8 GHz, the 12th harmonic of the LHC RF system. At this frequency, upper and lower sideband Schottky signals do not overlap, the pickups satisfy the minimal beam aperture requirement of 60x60 millimeters, and the vacuum vessels would fit between the 194 millimeters

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beam center-to-center spacing. The LHC system [7] was installed in 2007 and successfully commissioned in the first physics run in 2010.

PICKUP DESIGN CONSIDERATIONS

The pickup is essentially a sandwich of three waveguides separated by coupling slots in a thin metal foil, Figure 2. The center waveguide is that in which the beam circulates. The output of the outer two waveguides when added 180 degrees out of phase with the use of an external microwave hybrid circuit provides the difference mode containing transverse characteristics of the beam. The pickup is bidirectional, which allowed it to be used for both protons and antiprotons in the Tevatron. The hybrid output sum mode signal is also utilized for a beam present witness signal for the gating system. Bandwidth selection of the individual systems was based on the bunch spacing. In the Fermilab Recycler, beam is bunched by barrier buckets, which do not present a significant bandwidth restriction. The Tevatron bunches were in buckets that were 18.8 nanoseconds in length and separated by 21 buckets, or 396 ns. The LHC has an ultimate bunch spacing of 25 ns.

Both the Recycler and Tevatron have the identical pickups centered at 1.7 GHz. A 3 dB bandwidth of 100 MHz was chosen to provide adequate response for the bunch-by-bunch gating requirement in the Tevatron. In the Tevatron, both protons and antiprotons circulated on separated helical orbits through the same pickup. While the pickup was measured to have a directivity of 12 dB, it was imperative to locate the pickups in a region of the Tevatron where protons and antiprotons do not intersect. Preferably in a spot where crossings are tens of nanoseconds apart, easing the gating speed requirements. Such a location would allow the gating system to cleanly separate the two beam signals. The best common mode rejection occurs for beam that traverses the pickup on the electrical center orbit. Unfortunately, in the Tevatron with helical orbits, both beams cannot be on this same orbit, resulting in larger common mode for any off axis beam.

For the LHC, the minimum aperture specification is 60x60 millimeters. A further restriction was the pickup was not to be moved physically by means of remotely controlled motorized stands due to large stored beam energy. The LHC has two separate beam pipes; hence, location was not as critical as in the Tevatron as there is no bunch crossing restrictions. Four pickups were constructed, two in each beam located near access point 4.

SIGNAL PROCESSING

Early Tevatron bunched beam cooling measurements displayed large coherent signals at harmonics of the revolution frequency at microwave frequencies. A simple Fourier transform of the beam envelope would indicate that revolution lines should not be present at frequencies above 1 GHz. This turns out not to be the case as intra bunch instabilities [8] generate coherent lines observed in the Tevatron at FNAL, SPS & LHC at CERN, RHIC at Brookhaven, and HERA at DESY in Hamburg. To reduce any nonlinearities and intermodulation distortion, the processing electronics must have large instantaneous dynamic range to cope with these coherent harmonics.

All of the relevant diagnostic characteristics of the beams are contained in every revolution harmonic. The final baseband bandwidth therefore does not need to exceed the width between two revolution lines. The gating requirement, though, requires significant bandwidth to allow individual bunch gating capability. The Fermilab systems have a pickup bandwidth of 100 MHz. The tighter 25-nanosecond bunch spacing in the LHC required a pickup with 200 MHz minimum bandwidth. Once gating is accomplished, the need for wideband signal processing is no longer essential. Band limiting cavity and crystal filters render a reduced bandwidth thus improving noise performance and limiting the integrated power from multiple revolution bands.

The pickup preamplifier should have the lowest available noise figure. However, more importantly, a very high output power compression rating to cope with the large dynamic range. These two characteristics are not normally found simultaneously in commercially available amplifiers and a compromise is made in favor of compression levels.

In keeping with the requirement to retain chromaticity measurements a triple down conversion narrow band crystal filter single side band system was designed to have a 100 dB instantaneous dynamic range. Each of the revolution lines contains details of revolution frequency, tune, momentum spread, and chromaticity that are easily resolved in the frequency domain. Fermilab utilized commercial FFT baseband analyzers while CERN chose to use in house developed FFT hardware.

Conventional high-level double balanced mixers are used for each stage of down conversion. The high level mixer is required due to large dynamic range of the Schottky signal. More importantly is the selection of local oscillators (LO) for their phase noise performance. The transverse Schottky signals are typically 10 dB or less above the system noise floor. The machine revolution frequencies range from 89 KHz (Recycler), 47 KHz (Tevatron) to 11 KHz (LHC) indicating the betatron sidebands will be closely spaced in frequency to the revolution lines. Figure 3 shows a typical IF at 400 MHz in the Tevatron utilizing two different sources for the first LO. The poor phase noise due to the LO in the green trace virtually obscures the Schottky signal. The phase noise on the blue trace clearly demonstrates the need for clean LOs as they establish the minimum detectable signal. Phase noise of oscillators is worse closer to the fundamental frequency output. With the lower revolution frequency at the LHC, sidebands are within a few KHz of

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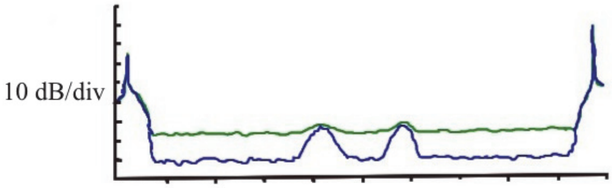
the revolution lines forcing the use of premium performance LOs at each stage of down conversion. Most recent tunes in the Recycler, Tevatron, and LHC are of order 0.465, 0.585 and 0.320 respectively.

The final stage of down conversion employs 15 KHz crystal filters, two in series for maximum out of band rejection. For the LHC this bandwidth will pass at least one revolution line. In the Tevatron, LO frequencies are chosen to center the two-betatron sidebands in the pass band and no revolution lines are present.

An extensive system noise analysis was performed for the signal processing chain. A 100 dB instantaneous dynamic range was achieved by the careful selection of components, matching, and electromagnetic shielding. A calibration signal is also injected into the processing electronics as a diagnostic aid for monitoring gain variations over time. The Tevatron system utilizes both up and down stream pickup outputs for proton and antiproton signals. The Tevatron calibration signal is injected before the first preamplifier. In the LHC, only one output from the pickup is used, leaving the other available for calibration signal injection. This has the added benefit that the pickup response and electronics transfer function can be measured in the calibration mode.



Center Frequency 400 MHz, Span 50 kHz

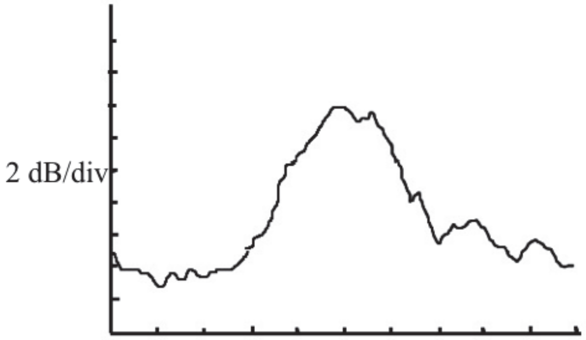
Figure 3: Effect of local oscillator phase noise on system sensitivity. 400 MHz IF sample front panel test point of Tevatron Schottky. Green HP8341A as first LO, Blue IFR 2042 as first LO.

PERFORMANCE

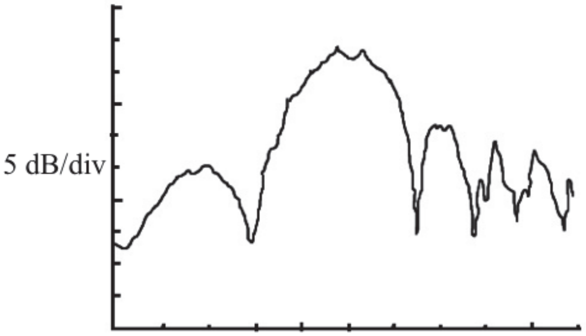
Recycler

The coherent nature of bunched beams complicates the measurement of the pickup's beam sensitivity. In the early stages of commissioning the Recycler prior to the availability of antiprotons, it was possible to inject reverse protons. Due to the bi-directionality of the pickups, the spectral response could easily be measured on debunched coasting beam, Figure 4.

In the Recycler, the Schottky diagnostic was the principal measuring tool for tunes and momentum spread. With a single species of Recycler beam, i.e. antiprotons, it is possible to dramatically reduce the common mode signal by centering the pickup on the beam. A power meter is employed to minimize pickup power across the band. Some 3 to 6 dB total power reduction is typical.



Center Frequency 1.71 GHz, Span 500 MHz
Peak Value -74 dBm



Center Frequency 1.77 GHz, Span 500 MHz
Peak Value -55 dBm

Figure 4: Spectral response of 1.7 GHz Schottky pickup for 1.4 x 10^{11} DC coasting proton beam in the Recycler. Top difference mode, bottom sum mode.

At 1.7 GHz, the Schottky system operated in the same band as the longitudinal stochastic cooling system. At selected intervals when the Schottky tune is measured, the cooling system is gated off to reduce signal suppression cross talk between the cooling and Schottky systems. The Recycler tune is close to the half integer. Schottky bands begin to overlap at 1.7 GHz with beam currents exceeding $1x10^{12}$. The resolution bandwidth of the FFT must be set sufficiently narrow (<3KHz) to resolve the two sidebands. Measurements of both planes took about a minute with the controls application program.

Tevatron

The Tevatron Schottky system was in continuous operation 2003-2011. Before the commissioning of this instrument, there was no means of measuring the antiproton tunes in the Tevatron. Co-rotating beams of protons and antiprotons in the same beam pipe made for difficult separation of the two signals. The high bandwidth of the Schottky system along with location of the pickups away from crossing points allowed a gating system to separate the signals. The primary function is measurement of tunes at collisions through the store, Figure 5. This is accomplished with an open access client (OAC) application that continually monitors and logs

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tunes, chromaticity, and momentum spread. Most notably, the beam-beam antiproton tune shift is adjusted based on the tune measurement. Figure 6 shows the variation in tune before and after using the Schottky tune measurement for antiproton tune compensation over a one-month period. The monitor guides the operations staff in manual adjustments of tune, keeping tune variation to a 0.005 window shown in the second half of the plot.

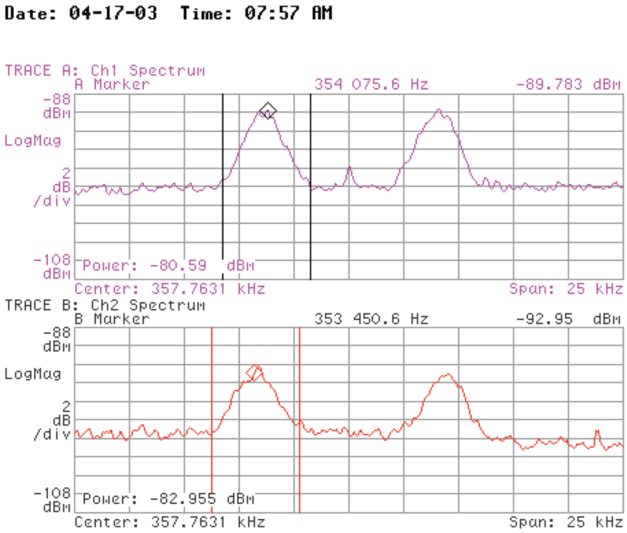

Figure 5: Tevatron Schottky antiproton tune measurement, top Horizontal, bottom Vertical.

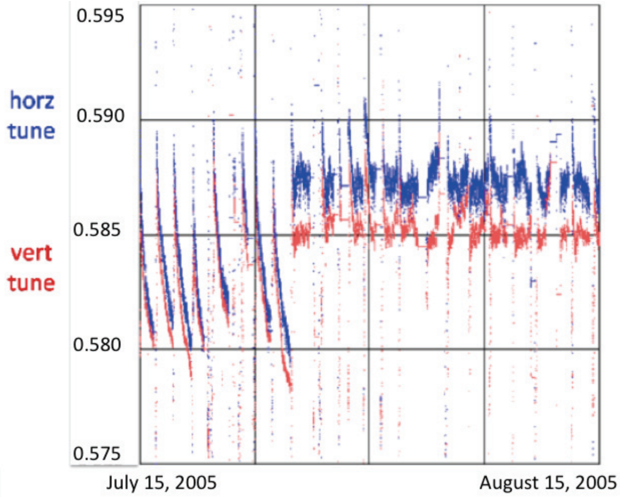

Figure 6: Tevatron antiproton beam tune shift. When the 1.7 GHz Schottky monitor was used beginning July 2005 to correct antiproton beam-beam tune shift, the tune excursions were minimized by manual tune change resulting in increased beam lifetime.

The individual bunch gating capability of the Schottky system has been utilized in studies with the electron lens. The electron lens has been used to alter the tunes of individual bunches. Measurement of the induced tune shift is accomplished with the Schottky monitor. The Schottky monitor has also been used to study the tune variation between different bunches in the three 12 bunch trains of a typical store. Figure 7 shows significant tune and chromaticity variation for leading and trailing bunches [9, 10]. In the Tevatron, proton bunch intensities of $3x10^{11}$ and antiproton intensity of $8x10^{10}$ were nominal. With averaging, single bunch protons and two or more bunches of antiprotons are easily resolved.

The average tune spread reported by the Schottky OAC agrees well with the bunch length based momentum-spread measurement for protons, but for antiprotons, a small offset has been observed early in stores. This can be attributed to the additional tune spread arising for beam-beam, since it scales as the beam-beam parameter and has about the expected magnitude.

In the Tevatron, for the first few minutes after beams are set into collisions, the Schottky beam signals appear to be “boiling” furiously as seen in both time and frequency domains and stable tune measurements have not been reliable. A number of studies and hardware modifications to the system have been attempted to alleviate this condition, but it does not appear to be due to signal compression or nonlinearities in the processing electronics.

LHC

Initial commissioning of the LHC Schottky system was completed in October of 2010 and is now considered an operational instrument for CERN’s proton-proton/lead-lead collider. Tune and chromaticity measurements for both protons and lead ions has been demonstrated and verified against other instruments measuring these same parameters. Figures 8 shows spectra for protons and lead ions. Note that with protons, the coherent line is sometimes present on the betatron sidebands. The resolution of the CERN system indicates that these lines are synchrotron satellites. These sideband satellites have not been observed in the Tevatron. The LHC Schottky system has also proven to be a valuable measurement tool during the slow beam energy ramp.

The measurement of chromaticity is particularly useful at injection energy, where the decay of the higher mode dipole component translates into a chromaticity drift, which, if left uncorrected, can lead to negative chromaticity and instability. Lead ion signals were significantly cleaner than proton signals and seemed to suffer less from coherent contributions to the transverse spectra, allowing an on-line measurement of tune and chromaticity throughout the accelerator cycle. The proton spectra suffered from the added complication of the RF longitudinal blow-up. The beam blow up being performed purposely to maintain a relatively long bunch length throughout the ramp. This produced a wide longitudinal component at the revolution line, which completely swamped the transverse Schottky bands. As has been observed at the Tevatron, the cleanest spectra were obtained several tens of minutes after initiating collisions for protons.

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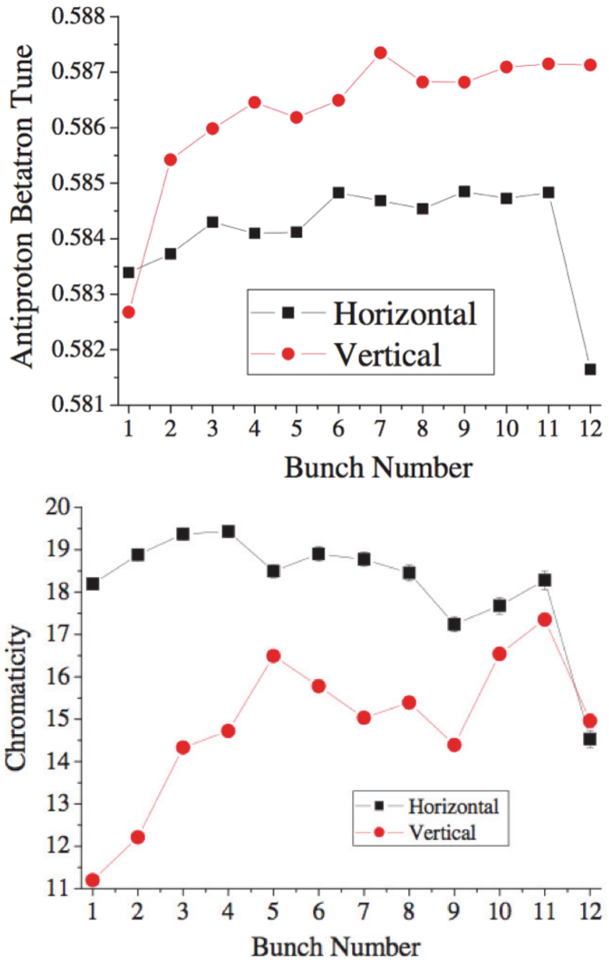

Figure 7: Tevatron horizontal and vertical antiproton tunes and chromaticity versus bunch number.

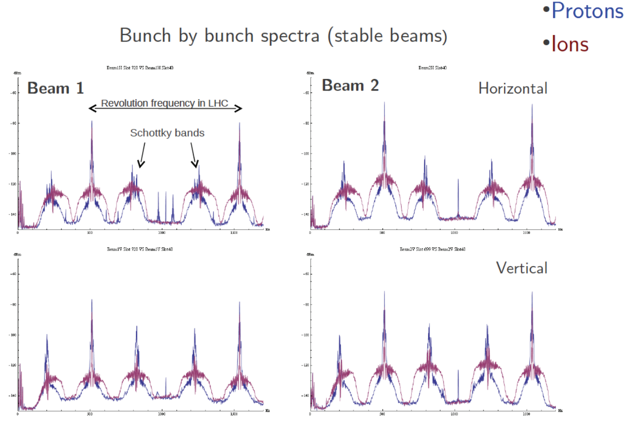

Figure 8: LHC Schottky spectra for protons and lead ions.

An added advantage of the LHC Schottky monitor, with its high detection frequency at 4.8 GHz, is its immunity to the effects of the transverse damper. The transverse damper system is being used at a relatively high gain to combat instabilities and emittance blow-up. The damper induced interference to the standard tune system is not observed with the Schottky system. The LHC Schottky system is therefore being considered as a serious alternative to the standard tune system for providing data to auto tune feedback. Implementation for tune feedback will require a faster tune acquisition than is currently possible with existing data acquisition hardware plus a robust measurement throughout the ramp, even in the presence of longitudinal blow-up.

CONCLUSIONS

Tevatron and Recycler Schottky systems were in continuous use at Fermilab until September 30, 2011. The Schottky system in the Recycler was the main mechanism for tune and momentum spread measurements. The ability to adjust for beam-beam tune shifts in the Tevatron yielded improved beam lifetimes and integrated luminosity. At CERN, the Schottky system is being considered as a prime measurement tool for tune and chromaticity [11].

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