IMPROVEMENTS TO THE LHC SCHOTTKY MONITORS

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Abstract

The LHC Schottky monitors have the potential to measure and monitor some important beam parameters, e.g. tune, momentum spread, chromaticity and emittance, in a non-invasive way. We present recent upgrade and improvement efforts of the transverse LHC Schottky systems operating at 4.81 GHz. This includes optimization of the slotted waveguide pickups and a re-design of the RF front-end electronics to detect the weak, incoherent Schottky signals in presence of large, coherent beam harmonics.

INTRODUCTION

The theory of bunched beam transverse Schottky signals reveals the measurement of machine parameters, such as tune, chromaticity, emittance, etc. based on the observation of coherent and incoherent motion of the bunched particles [1]. The associated dipole moment of each particle, following betatron and synchrotron motion, can be expressed as Fourier series, showing upper (usb) and lower (lsb) betatron sidebands around each revolution harmonic \( h \), which further splits into synchrotron satellites.

The \textit{Fourier} representation hints to perform the observation of these tiny particle fluctuations in the frequency domain. Figure 1 shows a downconverted Schottky spectrum \((h = 427746, f_{\text{rev}} = 11.245 \text{ kH}z)\) for a bunch of \( n \approx 10^{11} \) protons (charge state \( z = 1 \)) in the LHC at injection energy. In practice, even with a very well centered beam, the longitudinal common mode revolution harmonics are always present, and usually dominant. In this low-resolution measurement the synchrotron sideband modulation is “smeared out” to the usb and lsb incoherent Schottky signal “humps”. Clearly visible on top of these incoherent signal humps are the coherent betatron sidebands, whose intensity is dependent on the longitudinal bunch shape and amplitude of any residual coherent oscillations. These allows the measurement of the fractional betatron tune \( q = f_{\beta}/f_{\text{rev}} \).

The chromaticity \( \dot{Q} \) is derived from the different widths \( \Delta f_{\text{usb}}, \Delta f_{\text{lsb}} \) of the respective usb and lsb Schottky humps.

\[
\dot{Q} = \eta \left( \frac{\Delta f_{\text{lsb}} - \Delta f_{\text{usb}}}{\Delta f_{\text{lsb}} + \Delta f_{\text{usb}}} + q \right) \approx \eta h \frac{\Delta f_{\text{lsb}} - \Delta f_{\text{usb}}}{\Delta f_{\text{lsb}} + \Delta f_{\text{usb}}} \tag{1}
\]

with \( \eta \) being the phase slip factor, which is 3.183e-4 for the LHC. The approximation is true for \( h \gg \eta \) and \( \Delta f_{\text{lsb}} - \Delta f_{\text{usb}} \neq 0 \). At 4.81 GHz \( h \approx 4.28e5 \), so that \( \eta h \approx 136 \), implying that a 1% difference in width represents 1 unit of chromaticity. The momentum spread \( \Delta p/p \) is proportional to the average width of the sidebands

\[
\frac{\Delta p}{p} \propto \frac{\Delta f_{\text{lsb}} + \Delta f_{\text{usb}}}{2 f_{\text{rev}} h \eta} \tag{2}
\]

and the emittance can be estimated from the total signal power contained in a given sideband hump, with \( A_{\text{usb}} \Delta f_{\text{usb}} = A_{\text{lsb}} \Delta f_{\text{lsb}} \). This, however, requires independent calibration.

THE LHC SCHOTTKY MONITOR SYSTEM

The LHC Schottky monitoring system (Fig. 2) was designed and built in frame of the US LARP collaboration with Fermilab [2, 3]. An operation frequency of 4.8 GHz was selected as the best compromise between avoiding overlapping Schottky sidebands at very high frequency, and being within the single bunch coherent spectrum at low frequency. A symmetric arrangement of slotted waveguide couplers is used to provide a broadband Schottky beam pickup, followed by an RF front-end with narrowband, triple-stage downconversion and a 24-bit audio digitizer based DAQ system. While the 200 MHz bandwidth of the beam pickup offers single bunch time resolution, selected by a fast gate switch, the following low-noise receiver has a final bandwidth of \( \approx 15 \text{ kHz} \), slightly larger than the 11 kHz LHC revolution frequency. The LHC is equipped with four such Schottky monitoring systems, a horizontal and a vertical unit for each beam.

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During LHC Run 1 the LHC Schottky monitors performed very well with lead ion beams (PB82+), due to the fact the total Schottky signal power density in the sidebands scales with $z^2$. Unfortunately with protons the incoherent Schottky signal levels were often too close to the noise floor to extract useful beam parameters. The amplifiers in the RF front-end also suffered from saturation effects due to high level, out-of-band common mode signals. Despite common mode suppression of more than 40 dB through the use of a $\Delta$-hybrid, the intensity of the residual coherent harmonics were much higher than expected, linked to the non-Gaussian particle distribution of the bunch. An instantaneous dynamic range between incoherent Schottky signals and common mode revolution harmonics over 100 dB is therefore required, which is a major challenge for the RF signal processing.

**SCHOTTKY BEAM PICKUP**

The slotted rectangular cross-section waveguides of the Schottky beam pickup couples to the TEM field of the beam through their fundamental TE01 mode. The dimensions of the array of 270 rectangular slots was optimized through a semi-analytical approach [4], to obtain a tight coupling to the beam, while ensuring the phase velocity of the TE01 $\Delta$-mode $v_p \approx c_0$. Both ends of each waveguide are equipped with a “mode-launcher”, which is a waveguide(WG)-to-coaxial transition [5], the downstream pair act as signal ports, while the upstream pair is used to feed a test tone signal for calibration and maintenance purposes.

![Figure 3: Return-loss of the optimized waveguide-to-coaxial mode launcher.](image)

Beam measurements and a detailed RF verification of the four Schottky pickups revealed a higher than anticipated return-losses (10 dB) from the WG-coaxial mode launchers, initiating a redesign. All four Schottky monitors received a complete overhaul during the long LHC shutdown of 2014. This included incorporating a new WG-coaxial mode launcher, as well as a variety of other mechanical and RF improvements. Figure 3 shows the $|S_{11}|$ return-loss results of the improved mode launcher, comparing simulations and measurements under different test conditions [6]. Due to the tolerances of the coaxial feedthroughs, each WG-coaxial launcher had to be fine tuned by some bending and rotating of the coaxial pin to achieve the maximum performance.

The transfer response (Fig. 4) between beam and downstream output ports indicates an operation frequency sweet spot near 4.7 GHz for better suppression of the common mode (sum) signal. This was, however, not confirmed through beam measurements. While the redesigned WG-coaxial launcher improved the RF properties of the Schottky pickup, an $|S_{31}|$ isolation measurement after installation between the output ports discovered substantial remaining reflection effects, probably caused by the rather low waveguide cutoff frequency of the beam ports ($f_{TE01} = 2.5$ GHz).

![Figure 4: Simulation of the Schottky pickup transfer response.](image)

Figure 5 shows ~20 dB isolation with well terminated beam ports under laboratory measurement conditions (green and blue traces), but strong coupling $>10$ dB after installation (red trace), which is explained by reflections due to discontinuities in the beam pipe.

![Figure 5: Remaining isolation between the output ports before and after installation of the Schottky beam pickup.](image)

**RF SIGNAL PROCESSING**

Figure 6 gives an overview of the RF hardware for the processing of the Schottky signals. It consists out of an RF front-end for bunch gating and signal conditioning at 4.81 GHz, which is located in the LHC accelerator tunnel. This is followed by a RF back-end triple-stage downconverter located in the LHC alcove along with the DAQ electronics.

The RF front-end is mounted directly on the Schottky beam pickup to keep the signal cables short for minimum insertion losses. A so-called “compensation path” consists out of a remote controlled attenuator and phase shifter, and is used to equalize the two output signals of the Schottky beam pickup to minimize the common mode signal contribution at the output of the $\Delta$-hybrid. This compensation path was kept unchanged, however, most other parts of the RF front-end were substantially modified to better accommodate the dynamic range requirements and single bunch gating capabilities.
The RF back-end received only minor modifications, e.g. the low-pass filter of the 1st 400 MHz IF stage was replaced by a band-pass filter for image rejection purposes, and the original 4.4 GHz fixed frequency 1st LO can now also be varied. Beam studies at different operating frequencies in the range 4.5-4.9 GHz, supported by a YIG band-pass filter in the RF front-end, did not discovered a more favorable operating frequency than 4.8 GHz. A gate-switch is used for noise-reduction, with the switching time matched to the ∼1 μs decay time of the cavity filter in the RF front-end.

RF Front-End Modifications

As Fig. 6 shows, the RF front-end is split into a low-gain (12 dB) wide-band (70 MHz) section before the coaxial switch, followed by a high-gain (45 dB) narrow-band (1.4 MHz) section. The wide-band signal can be temporarily switched to a signal analyzer to minimize the common-mode signal by tuning the compensation path.

The main noise contribution originates from the signal attenuation, defined by the insertion loss of ∼10 dB between beam pickup electrode and input of the low-noise amplifier (LNA), plus the LNA noise figure of NF ≈ 1.2 dB.

Fast Gate-Switch Following the Δ-hybrid, a DC-28 GHz SPDT gate-switch with ∼1 ns switching times is used to select one or more bunches from the LHC beam. VNA-based measurements around 4.8 GHz show an insertion loss of 2 dB, a return loss of ∼14 dB, and isolation >50 dB. The switch can handle rather high signals up to +20 dBm (0.1 dB compression), which is important to avoid saturation effects due to the high common mode signal contents it has to handle.

Figure 7 shows the time domain response of the Schottky system at the Δ-hybrid output using a fast oscilloscope (20 GHz BW, 60 GS/s). The upper trace shows a section of a LHC bunch train with 100 ns spacing, the lower trace zooms the waveform response of the first bunch. A single bunch response time of ∼10 ns is observed, followed by some unwanted reflection effects, as expected from the VNA measurements shown in Fig. 5. A dedicated switch driver (gate CTRL) was developed for fine control of the switching times of the gate pulse, synchronized with the accelerator RF, to precisely extract the Schottky bunch signal from a given bunch.

Fast Gate-Switch

Following the Δ-hybrid, a DC-28 GHz SPDT gate-switch with ∼1 ns switching times is used to select one or more bunches from the LHC beam.
A self-built 2-stage *Bessel* band-pass filter, based on interdigital airline resonators [7] was found to be a good compromise in terms of insertion loss, selectivity, and impulse response. Figure 8 (a) compares the measured and simulated $|S_{21}(f)|$ transfer function, while Fig. 8 (b) shows the corresponding measured time-domain response $s_{21}(t)$. With a total decay time of $5\tau \approx 25$ ns, this design gives some flexibility to locate this filter either before or after the fast gate-switch.

**4.8 GHz Cavity Band-pass Filter** After gating, there is no need for a ns-scale time resolution, hence narrowband filtering was applied to minimize integrated spectral power. A modified pill-box cavity was used as a single stage bandpass filter with a bandwidth of $\leq 0.03\%$.

A mode chart for an ideal cylindrical resonator (Fig. 9) allows its height $h$ to be optimized for maximum separation of the eigenmodes ($h \approx 50$ mm, $r = 46.5$ mm for $f_{TE011} \approx 4.8$ GHz). Modifications on both end caps help to detune the degenerated $TM_{111}$-mode [8], and provide a simple solution to fine-tune $f_{TE011}$. With brass as the cavity body material a quality factor $Q_0 \approx 9300$ is obtained, while tuning the coupling loops to a minimum insertion loss of $\sim 2.2$ dB gives $Q_L \approx 3700$, corresponding to a total signal decay time of $\sim 1 \mu s$. Silver-plating would approximately double $Q_0$, as well as the decay time, but the cavity then becomes more sensitive to variations of the ambient temperature in the accelerator tunnel.

**FIRST RESULTS AND OUTLOOK**

An example of first results with beam for a refurbished *Schottky* monitor is presented in Fig. 1, and have been discussed recently in more detail in [9]. A new peak detection algorithm allows the extraction of the coherent tune with a resolution $< 10^{-3}$ while different fitting algorithms are currently under study for chromaticity calculation. The improved *Schottky* diagnostics are also helping during machine development periods for specific studies such as measuring the beam-beam tune shift, effects of wakefields on the tune, synchrotron tune shifts vs. RF manipulations, etc.

For bunched proton beams the high common mode coherent revolution harmonics and the reflection effects remain a challenge, and still present some limitations for a simple, turn-key operation of the *Schottky* systems.

**REFERENCES**


