IMPROVEMENTS TO THE LHC SCHOTTKY MONITORS

M. Wendt*, M. Betz, O.R. Jones, T. Lefevre, T. Levens, CERN, Geneva, Switzerland

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 wave-guide 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.

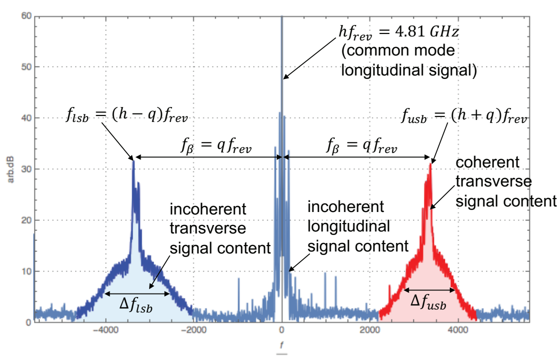


Figure 1: Typical LHC *Schottky* spectrum.

The *Fourier* representation hints to perform the observation of these tiny particle fluctuations in the frequency domain. Figure 1 shows a downconverted *Schottky* spectrum ($h = 427746$, $f_{\rm rev} = 11.245$ kHz) 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 $q = f_\beta / f_{\rm rev}$.

* manfred.wendt@cern.ch

The chromaticity $\acute{Q}$ is derived from the different widths $\Delta f_{\rm usb}$, $\Delta f_{\rm lsb}$ of the respective usb and lsb *Schottky* humps.

$$\acute{Q} = \eta \left(h \frac{\Delta f_{\rm lsb} - \Delta f_{\rm usb}}{\Delta f_{\rm lsb} + \Delta f_{\rm usb}} + q \right) \approx \eta h \frac{\Delta f_{\rm lsb} - \Delta f_{\rm usb}}{\Delta f_{\rm lsb} + \Delta f_{\rm usb}} \tag{1}$$

with η being the phase slip factor, which is 3.183e-4 for the LHC, The approximation is true for $h \gg \eta$ and $\Delta f_{\rm lsb} - \Delta f_{\rm usb} \neq 0$. 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

$$\frac{\Delta p}{p} \propto \frac{\Delta f_{\rm lsb} + \Delta f_{\rm usb}}{2 f_{\rm rev} h \eta}, \tag{2}$$

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

THE LHC SCHOTTKY MONITOR SYSTEM

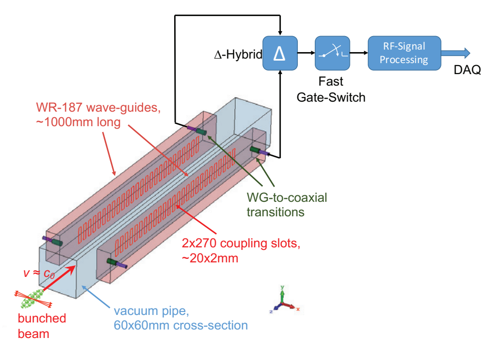


Figure 2: Simplified overview of the LHC *Schottky* monitor system (beam pickup not to scale).

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 down-conversion 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 ~15 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.

ISBN 978-3-95450-177-9

During LHC Run 1 the LHC *Schottky* monitors performed very well with lead ion beams (PB^{82+}), due to the fact the 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 Δ-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 TE_{01} 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 TE_{01} Δ-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.

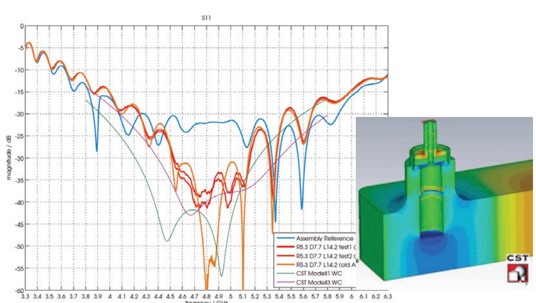


Figure 3: Return-loss of the optimized waveguide-to-coaxial mode launcher.

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 feedhroughs, 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 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.

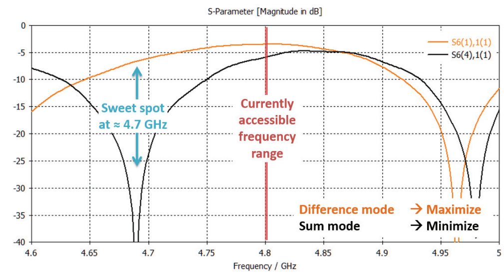


Figure 4: Simulation of the *Schottky* pickup transfer response.

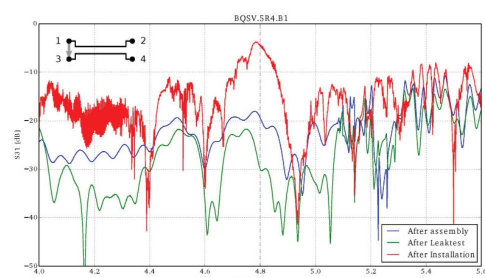


Figure 5: Remaining isolation between the output ports before and after installation of the *Schottky* beam pickup.

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 Δ-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.

ISBN 978-3-95450-177-9

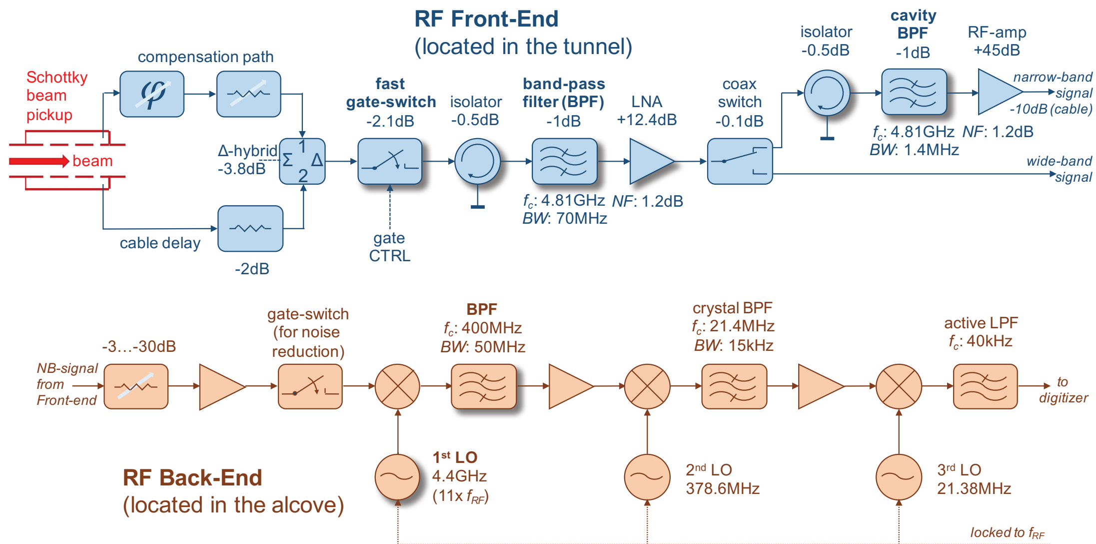


Figure 6: Simplified block schematics of the RF *Schottky* signal processing.

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 $\sim$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 $\sim$10 dB between beam pickup electrode and input of the low-noise amplifier (LNA), plus the LNA noise figure of $NF\approx1.2$ dB.

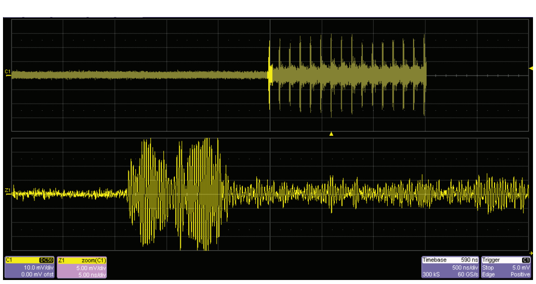
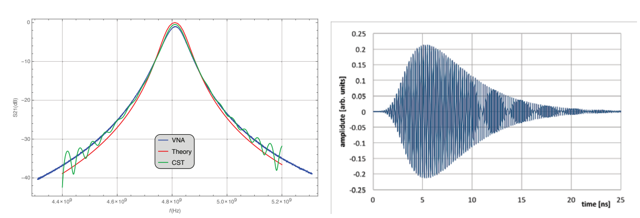


Figure 7: Bunched beam *Schottky* signals (time domain).

Fast Gate-Switch Following the Δ-hybrid, a DC-28 GHz SPDT gate-switch with $\sim$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 $\sim$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 GSPS). 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 $\sim$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.



(a) Frequency domain (b) Time Domain

Figure 8: Characteristics of the *Bessel* interdigital band-pass.

4.8 GHz Interdigital Band-pass Filter Different types of low insertion loss band-pass filters were tested, including a YIG-filter with a remote controlled adjustable resonance frequency. A band-pass filter of moderate bandwidth (10-15%) is required as a pre-selector, and helps to "clip" high common mode signal levels which otherwise tend to saturate the low-noise amplifier (LNA).

ISBN 978-3-95450-177-9

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 narrow-band 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 < 0.03 %.

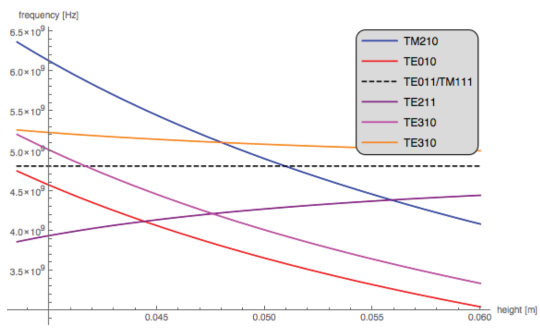


Figure 9: Mode-chart of an ideal "pill-box" resonator.

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 $f_{\mathrm{TE011}} \approx$ 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 ~2.2 dB gives $Q_L \approx 3700$, corresponding to a total signal decay time of ~1 μs. 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.

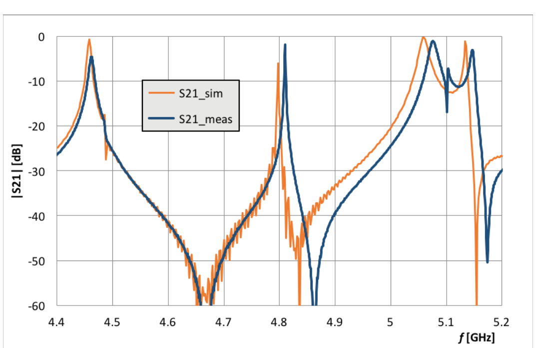


Figure 10: $|S_{21}(f)|$ transfer function of the cavity band-pass.

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 $<10^{-4}$ 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

[1] S. Turner, "Proceedings of the CAS", CERN, Geneva, Switzerland, CERN-95-06, Nov. 1995, Vol. II, pp.749-782.

[2] R. Pasquinelli, LARP-doc-482-v3, 2008, http://larpdocs.fnal.gov/LARP-public/DocDB/ShowDocument?docid=482

[3] F. Caspers., et.al., "The 4.8 GHz Schottky Pickup System", in *Proc. of Particle Accelerator Conf. (PAC'07)*, Albuquerque, NM, USA, June 2007, paper FRPMN068, pp. 4174–4176.

[4] D. McGinnis, "Slotted Wavguide Slow-Wave Stochastic Cooling Arrays", in *Proc. of Particle Accelerator Conf. (PAC'99)*, New York, NY, USA, March/April 1999, paper TUP100, pp. 1713–1715.

[5] D. Sun, "Design of LHC Schottky Pickup", Fermilab internal document, RF Technote, April 2006.

[6] M. Ehret, "Untersuchung eines breitbandigen Koaxial-Hohlleiteruübergangs für einen Schottky-Strahldiagnosedetektor", Ms.Sc. thesis in German language, University of Applied Sciences Offenburg, Germany, December 2013.

[7] G. Matthaei, L. Young, E.M.T. Jones, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures", McGraw-Hill, 1964, pp. 616–626.

[8] B. Yassini, et.al., "A Ka-Band Fully Tunable Cavity Filter", IEEE Trans. on Microwave Theory and Techniques, Vol. 60, No. 12, Dec. 2012, pp. 4002–4012.

[9] M. Betz., et.al., "Upgrade of the LHC Schottky Monitor, Operational Experience and First Results", in *Proc. of Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper MOPMB060, pp. 226–228.

ISBN 978-3-95450-177-9