



Large Hadron Collider Project

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THE 4.8 GHZ LHC SCHOTTKY PICK-UP SYSTEM

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Abstract

The LHC Schottky observation system is based on traveling wave type high sensitivity pickup structures operating at 4.8 GHz. The choice of the structure and operating frequency is driven by the demanding LHC impedance requirements, where very low impedance is required below 2 GHz, and good sensitivity at the selected band at 4.8 GHz. A sophisticated filtering and triple down-mixing signal processing chain has been designed and implemented in order to achieve the specified 100 dB instantaneous dynamic range without range switching. Detailed design aspects for the complete systems and test results without beam are presented and discussed.

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frequency range of operation close to 5 GHz, where the coherent bunch spectrum is low and the pick-up impedance does not have too large an impact. At this frequency we are not yet limited by Schottky band overlap and pick-up (PU) technologies exist that permit a very high transverse sensitivity over a 100 to 200 MHz bandwidth with an acceptable length of the structure and suitable aperture. This amount of bandwidth is required to assure the possibility of gating on single bunches, which is not possible with a high Q cavity pick-up. Taking all these boundary conditions into account the choice of the PU hardware as well as the subsequent triple down conversion analog signal treatment chain is justified and will be discussed in the following sections.

INTRODUCTION

In order to optimize the integrated luminosity of the LHC, the beam emittance must remain as small as possible during the collision runs. Since the synchrotron radiation damping times required for any reduction in emittance are very long (of the order of 10 hours), the use of beam instrumentation that needs an excitation of the beam, hence leading to an increase in emittance, has to be limited [1]. This applies in particular to standard methods for the measurement of coherent tune and chromaticity that require various sources of beam excitation. A Schottky monitor on the other hand allows the measurement of these parameters without any additional excitation of the beam.

This monitor must comply with the stringent beam coupling impedance limitations of the LHC (longitudinal Z/n of the total machine $<0.1 \Omega$ up to 2 GHz). At the same time a very high transverse sensitivity is required in order to provide a reasonable signal to noise ratio even for a pilot bunch circulating in the machine. In order to meet those seemingly contradictory requirements we chose a

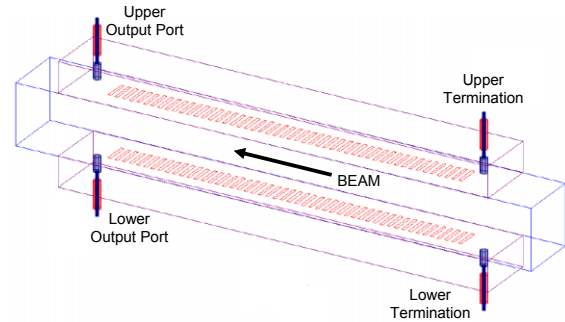


Figure 2: The slotted waveguide slow-wave structure schematic for the LHC Schottky pick-up. [4].

A detailed list of the LHC machine and beam parameters can be found in the literature [1, 2]. For the installation of this monitor in the tunnel a suitable location has been identified near point 4 in a normal conducting straight section meeting the required aperture of about 6 cm. Four monitors were installed, i.e. one for each plane of the two beams.

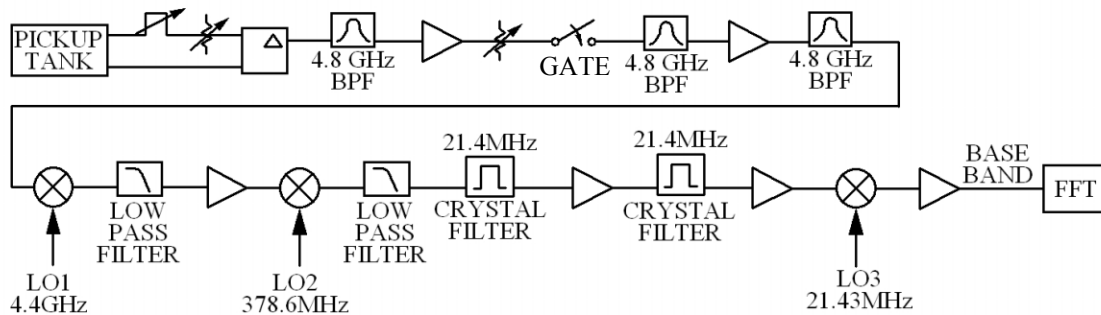


Figure 1: Block diagram of the signal processing system.

ANALOG SIGNAL TREATMENT CHAIN

A superheterodyne triple down conversion signal treatment chain has been designed and was implemented. This effort is required in order to provide a 100 dB instantaneous dynamic range without gain switching. Such triple down conversion concepts are also in use in high quality commercial instruments like certain spectrum analyzers for similar reasons. Such a large instantaneous dynamic range is required as there is a possibility that strong coherent signals may also appear in the bandwidth of interest. This is a typical phenomenon in large proton machines (SPS, Tevatron, RHIC). A simplified block diagram is shown in Fig. 2.

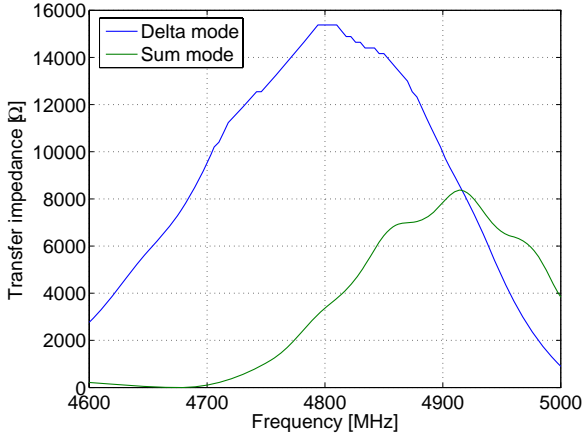


Figure 3: Simulated transfer impedance for LHC Schottky monitor.

Mechanical centering of the pick-up for maximizing common mode rejection was not an option as pickup motion could create an aperture restriction which is unacceptable in the LHC. Common mode signal reduction is therefore implemented by continuously adjustable mechanical attenuators and phase shifters before the signal recombination in the hybrids.

One important part of the RF front end is the gate to select single bunches or groups of bunches in the machine.

DETECTOR SENSITIVITY

The simulated transfer impedance of the LHC Schottky pick-up [7] is plotted in Fig. 3. The design has been centered at 4.8 GHz, which is an integer multiple of the 40 MHz revolution lines of the 25 ns bunch spacing of the nominal LHC beam. The transverse sensitivity of the pick-up has been designed to peak at this frequency. However, there is also a substantial longitudinal sensitivity at this frequency. From past experience it is estimated that the frequency offset between the simulated and the real pick-up response may be of the order of 50 MHz [6,7]. This was taken into account in the design of the signal treatment chain.

EXPECTED SIGNAL STRENGTH

The quantities of interest measured by the Schottky Monitor are the transverse Schottky sidebands. The signal to noise ratio (SNR) is given by the power of a Schottky sideband divided by the noise power in a relevant bandwidth. For this bandwidth several definitions are in use [2]; for the results presented below the ± 1 sigma width of the Schottky bands is employed.

The signal to noise ratio after combination of the two arms in a perfect hybrid is given for the longitudinal signals (sum output) as [2]

$$SNR_L = \frac{e^2 N f_0^2 Z_\Sigma}{k T \Delta f N_f}, \quad (1)$$

where e is the elementary charge, N the number of particles in the beam, f_0 the revolution frequency, k the Boltzmann constant, T the pick-up temperature, Δf the width of the Schottky band, Z_Σ the sum mode pick-up impedance and N_f the noise figure of the signal processing chain. The signal to noise ratio for the transverse signal (difference output of hybrid) is given as

$$SNR_T = \frac{e^2 N f_0^2 a_{rms}^2}{k T \Delta f} \frac{2 Z_\Delta}{d^2 N_f}, \quad (2)$$

where a_{rms} is the rms beam size, Z_Δ the Delta mode pick-up impedance and d the beam pipe diameter. The “old definition” of Z_Σ and Z_Δ are used here [5]. The expected sum and difference spectrum for a nominal LHC beam after combination in an ideal hybrid is shown in Figure 4. The noise figure of the signal processing chain is not included and the chromaticity was neglected on account of its small effect on the bandwidth and SNR. A thermal noise floor of -174 dBm/Hz is assumed, which adds to the expected signal from the beam.

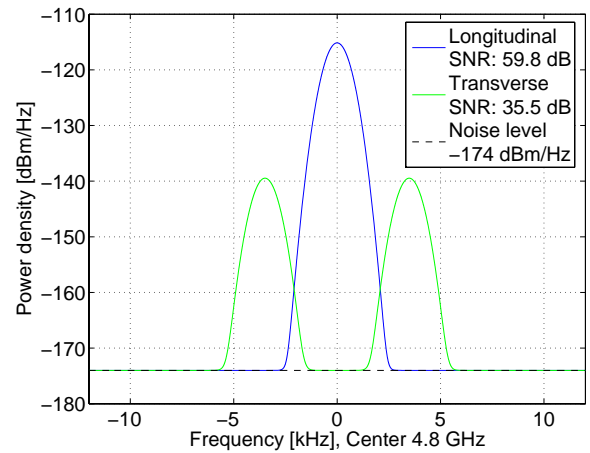


Figure 4: The calculated spectrum for a nominal LHC proton beam at injection.

shows the expected SNR for the different types of beams in the LHC. The noise figure of the signal processing chain and the possible improvements by gating

are not included. The range given for the pilot beam corresponds to minimum and maximum transverse emittance.

Table 1: Calculated SNR of the incoherent Schottky band for nominal beam and pilot in the LHC

		Schottky SNR [dB]	
		longitudinal	transverse
Nom. p ⁺ beam	inj.	60	36
	coll.	64	28
Pilot p ⁺ beam	inj.	12	-17 to -13
	coll.	16	-25 to -20
Nom. Pb ion beam	inj.	58	34
	coll.	64	28
Early Pb ion beam	inj.	49	24
	coll.	54	18

GATING

When the beam fills only a small fraction of the machine circumference, the pick-up will detect noise for most of the time. In particular for the pilot beam the noise level may become comparable to, or even bigger than, the Schottky sidebands. In this case the effective noise level can be decreased by gating, where the input signal is switched “on” only for a relatively short time during the passage of the beam. In practice, however, the input signal cannot be totally switched “off” and there will always be thermal noise coming from the terminating load and/or the losses of the switch itself. A cryogenic load could be used as a low-noise termination together with a lossless switch. A load at 1 K would then reduce the noise power by a factor 300 or 25 dB. However, in reality switches typically have transmission losses of about 2 dB, which renders such a concept non-applicable.

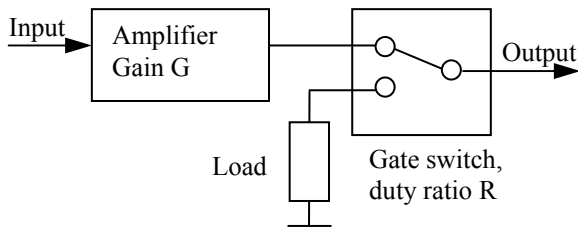


Figure 5: Gating after pre-amplification can be used to reduce the effective noise level.

The remaining option is to use sufficient pre-amplification before the gate (Figure 5). This way *both* the input noise and the beam signal are boosted. After this amplification, the gate switch can be used to pick out the amplified beam signal plus noise during the passage of the beam. The amplified noise during the rest of the time is removed by the gate and is replaced by the thermal noise of the gate in the “off” position, so corresponding to an effective reduction of the overall noise level.

The increase in signal-to-noise ratio due to gating, SNR' can be derived as:

$$SNR' = \frac{SNR_{OUT}}{SNR_{IN}} = \frac{G}{RG + 1 - R}, \quad (3)$$

with the amplifier gain G and the gate duty ratio R . For small G the gain in signal to noise is proportional to G , while for large G the gain in signal to noise converges to $1/R$. In LHC, with a gain before gating of 35 dB, it should be possible to improve the SNR through gating by about 30 dB for single bunch measurements.

CONCLUSION

In the framework of a LARP collaboration between FNAL and CERN a Schottky monitor system for the LHC has been designed and is now nearly completely installed. All test results can be found on a LARP web page [8]. Three stage down conversion has been implemented to achieve an instantaneous dynamic range of 100dB without gain switching, while a 24-bit Audio ADC followed by an FPGA implemented FFT algorithm [9] will be used to provide the continuous FFT spectra of the down converted baseband signals

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