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# Capabilities and Performance of the LHC Schottky Monitors

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## Abstract

The LHC Schottky system has been under commissioning since summer 2010. This non destructive observation relies on a slotted waveguide structure resonating at 4.8GHz. Four monitors, one for each plane of the two counter-rotating LHC beams, are used to measure the transverse Schottky sidebands Electronic gating allows selective bunch-by-bunch measurements, while a triple down-mixing scheme combined with heavy filtering gives an instantaneous dynamic range of over 100dB within a 20kHz bandwidth. Observations of both proton and lead ion Schottky spectra will be discussed along with a comparison of predicted and measured performance

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# CAPABILITIES AND PERFORMANCE OF THE LHC SCHOTTKY MONITORS

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### *Abstract*

The LHC Schottky System has been under commissioning since summer 2010. This non destructive observation relies on a slotted wave-guide structure resonating at 4.8 GHz. Four monitors, one for each plane of the two counter-rotating LHC beams, are used to measure the transverse Schottky side-bands. Electronic gating allows selective bunch-by-bunch measurements, while a triple down-mixing scheme combined with heavy filtering gives an instantaneous dynamic range over 100 dB within a 20 kHz bandwidth. Observations of both proton and lead ions Schottky spectra will be discussed along with a comparison of predicted and measured performance.

## INTRODUCTION

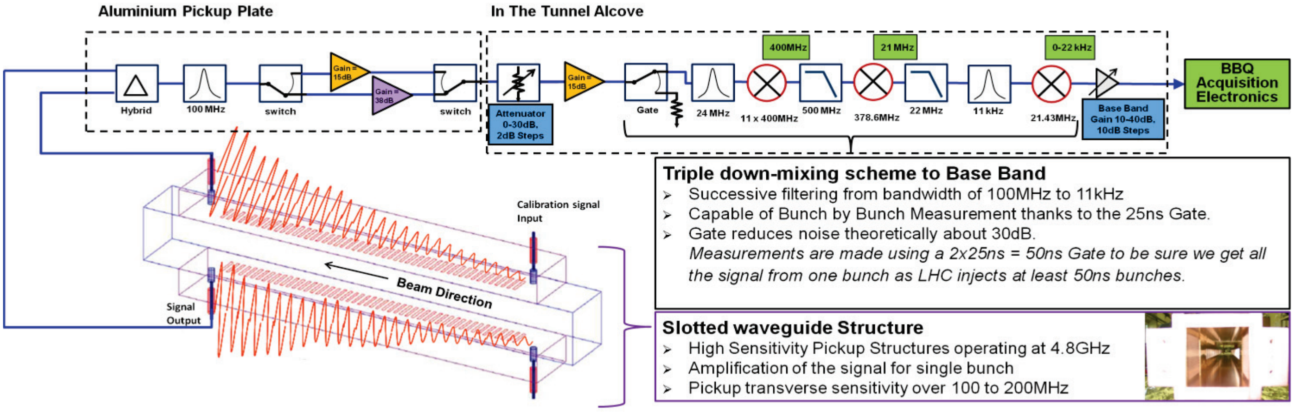
Using an appropriately sensitive detector, one can measure the individual transverse motion of particles in a beam, so-called Schottky Noise, and derive the tune, chromaticity, momentum spread and emittance [1,2]. Such Schottky monitors, designed by FNAL, US, are installed in the LHC for observation of transverse beam behaviour and have now produced their first results. This article will concentrate on a comparison of the theoretical and measured performance of the system and discuss some of its applications

## SIGNAL PROCESSING CHAIN

Using a high transverse sensitivity slotted wave guide pick-up operating at 4.8 GHz, the resulting difference (DELTA) mode is used to provide the transverse Schottky signal [3]. At this frequency the coherent bunch spectrum is significantly reduced, while the spectra are not yet limited by Schottky band overlap [4]. This allows the pick-up to have a large impedance without influencing the beam, and reduces the amount of coherent signal that the subsequent electronics needs to handle

The schematic of the analogue signal processing chain is shown in Fig 1. A triple down mixing scheme combined with heavy filtering gives an instantaneous dynamic range of over 100 dB within a 20 kHz bandwidth. This was a design criterion in order to be able to cope with any remaining coherent signals, which have been seen to be significant even well above the expected coherent bunch spectrum in many other machines. The presence of a Gate following the first amplifier stage, allows for a theoretical reduction in the noise equivalent to the amplifier gain for single bunch operation.

The acquisition in the base band is performed by the same electronics used for standard LHC tune measurements and is based on a 24bit ADC working at 44kHz (i.e ~4 times the LHC revolution frequency) [5].



**Triple down-mixing scheme to Base Band**

- Successive filtering from bandwidth of 100MHz to 11kHz
- Capable of Bunch by Bunch Measurement thanks to the 25ns Gate.
- Gate reduces noise theoretically about 30dB.

*Measurements are made using a 2x25ns = 50ns Gate to be sure we get all the signal from one bunch as LHC injects at least 50ns bunches.*

**Slotted waveguide Structure**

- High Sensitivity Pickup Structures operating at 4.8GHz
- Amplification of the signal for single bunch
- Pickup transverse sensitivity over 100 to 200MHz

Figure 1: The Analogue Processing Chain.

## SIGNAL TO NOISE RATIO STUDIES

### *Predicted Results VS Measured Performance*

The predicted performance of the Schottky system is documented in [6] for LHC design parameters. One can compute the predicted Transverse Schottky Signal to Noise Ratio with use of the Gate as:

$$SNR_T = \frac{e^2 N f_0^2 a_{rms}^2}{kT\Delta f} \frac{2Z_\Delta}{d^2 N_f} \frac{G}{R.G+1-R} \quad (1)$$

Where e is the elementary charge, N the number of particles, $f_0$ the revolution frequency (11245.475Hz), $a_{rms}$ the rms amplitude of individual particle oscillations (derived from the beam size at the pick-up location), $Z_\Delta$ the delta mode pick-up impedance (15500Ω from simulation), k the Boltzmann constant, T the pick-up Temperature (293K), Δf the ±1 sigma width of the Schottky band, d the beam pipe diameter (0.06m) and $N_f$ the noise figure of the acquisition chain. The final term takes into account the gain in SNR through gating, with G being the front-end gain and R the duty factor (defined as the time the gate is open divided by the revolution time).

Table 1 shows the measured and theoretical transverse Schottky SNR for different beams with and without gating. A pre-amplification of 38dB was used for all these measurements.

Table 1: Predicted Results VS Measured Performance

| | | *Injection* | *Collision* |
|---|---|---|---|
| Total Number of Particles | N | 1 pilot<br>1.11E+10 | 228 Nominal<br>2.67E+13 |
| Amplitude of Oscillations | $a^2_{rms}$ | 1.53E-06 | 2.28E-07 |
| Width of Schottky Band | Δf[Hz] | 440 | 467 |
| **$SNR_T$ [dB] No Gating** | **Theory**<br>**Measured** | **-7**<br>**not visible** | **18**<br>**18** |
| **$SNR_T$ [dB] with Gating** | **Theory**<br>**Measured** | **30**<br>**9** | **24**<br>**25** |

The first thing to notice is that the measured and calculated SNR agree well for those measurements performed without gating. This is even true for the case of the pilot intensity where the signal level obtained with gating turned on is seen to be -8dB with respect to the noise level with no gating (comparison of the red trace in Fig. 2 with the signal level of the Schottky bands in Fig. 2). Measurements making use of the gate, however, do not match with the calculated theoretical values for low intensity. This can be seen by looking at the Fig 2 which shows that gating on the pilot results in a gain of only 17dB instead of the expected 37dB.

Figs 3 and 4 show the results from a physics fill with 229 bunches during collision with and without gating respectively. Here the expected gain through gating is 6dB with 7dB measured. The measurement uncertainty is currently dominated by calculation of the Schottky sideband width and the emittance.

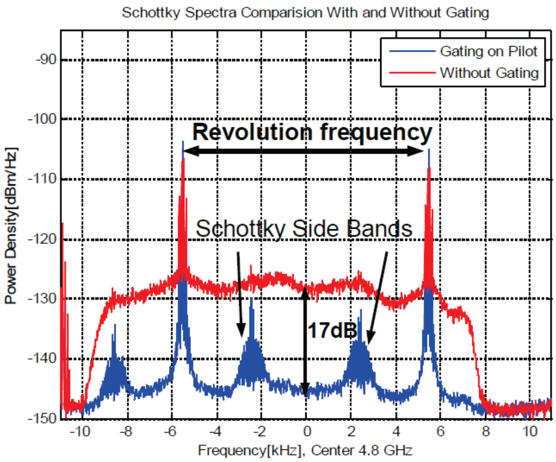


Figure 2: Gating or not on the Pilot at Injection.

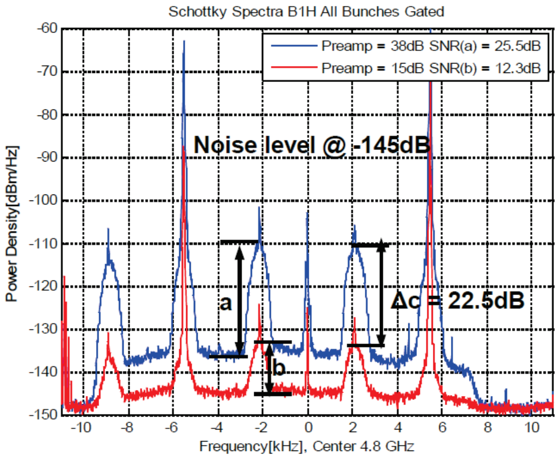


Figure 3: Gating on 229 bunches in the machine for two pre amplifier settings.

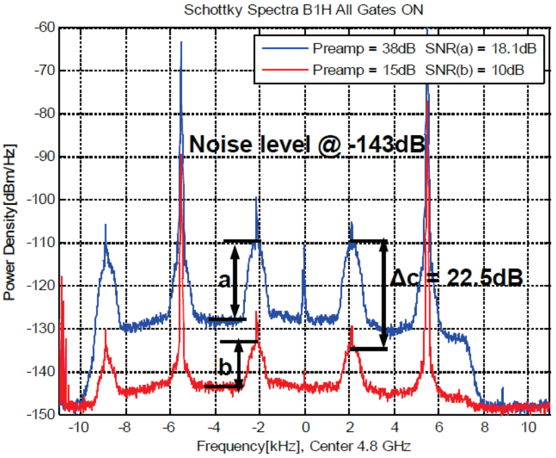


Figure 4: Measuring all 229 bunches in the machine without gating.

### *Close-up View of the Schottky Bands*

The Incoherent Schottky signal should increase proportionally to N, the number of particles in the beam, while coherent signals should increase quadratically, provided that the coherent tune of all particles is the same. Fig 5 shows the spectra obtained from a series of measurements performed by gating on more and more bunches. The underlying Schottky bands are clearly visible, with the sharp spikes being the coherent contribution from macroscopic bunch oscillations. Analysis of the Schottky signal level and SNR is presented in Fig 6. The linear evolution of Schottky signal with increasing bunch number is clearly visible. As the gate is opened around each new bunch, one would expect a constant SNR for all of these measurements. However, as was observed in the previous section, the full SNR improvement due to gating is not achieved, and hence the SNR deteriorates with fewer bunches.

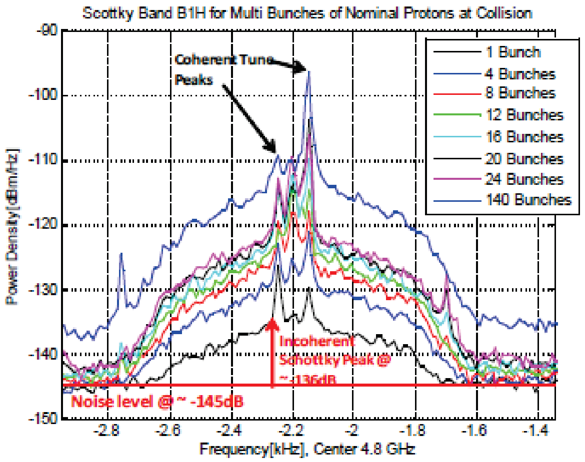


Figure 5: Incoherent Schottky Bands for protons at Collision.

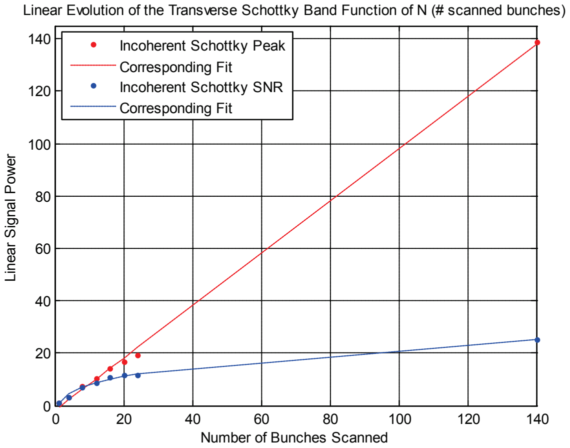


Figure 6: Linear Evolution of the Transverse Schottky peak (red) and of the SNR (blue).

## APPLICATIONS OF THE LHC SCHOTTKY MONITOR

Schottky monitors are currently the only instruments capable of providing bunch by bunch tunes in the LHC. This has proven useful for several studies, such as electron cloud build-up and beam-beam. Fig 7 shows an example from a head-on beam-beam study, where different beam-beam tune shifts measured by the Schottky monitor are clearly visible for bunches experiencing a different number of collisions.

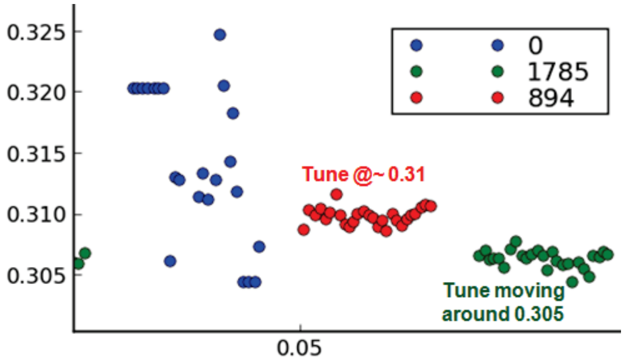


Figure 7: Schottky Tune measurement for pilot bunch (blue), nominal bunch with 1 collision (red) and nominal bunch with 2 collisions (green).

## CONCLUSION

Initial measurements suggest that the LHC 4.8GHz Schottky monitors are working to their design parameters during non-gated operation. Gating is seen to significantly improve the SNR but not to the expected extent for single bunches. It is believed that the current limitation is not in the front-end amplifiers, and hence the use of additional front-end gain before the gating will be tested in the near future.

These monitors are currently the only instruments in the LHC capable of measuring bunch by bunch tunes, and are extensively used for this purpose during machine development periods.

## REFERENCES

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