LATEST RESULTS FROM THE 4.8 GHz LHC SCHOTTKY SYSTEMS

M. Favier, O. R. Jones, CERN, Geneva, Switzerland

Abstract

This paper will present the latest results from the LHC 4.8GHz travelling wave schottky system, summarising measurements performed with both lead ions and protons during the 2011 and 2012 LHC runs. It will also describe attempts to improve the system architecture in order to make it more immune to the strong coherent lines observed with proton bunches even at these very high frequencies.

INTRODUCTION

Since 2010, the transverse LHC schottky systems have been undergoing commissioning. These sensitive detectors, designed by FNAL and installed in the LHC, are based on a slotted wave-guide structure resonating at 4.8GHz. They allow for a non-invasive observation of the tune, chromaticity, momentum spread and emittance [1, 2]. The theoretical performance of the system and its first results with proton beams has been described in previous publications [3, 4]. This article will present the measurements performed with lead ions during the 2011 LHC heavy ion run and make a comparison to protons measurements taken in 2012. It will also discuss methods of optimising the hardware in order to reduce the effects of the strong coherent lines still observed with protons bunches even at this high frequency.

SCHOTTKY SPECTRA WITH PROTONS AND LEAD IONS

The 2011 LHC heavy ion run gave the opportunity to compare the performance of these schottky devices when operating with lead ions and protons. These measurements were performed throughout the LHC cycle from injection, up the energy ramp, into collision and throughout the stable beams period (i.e. during physics data taking). As described in [3] an RF gate is used to allow acquisition of single bunches while maintaining a good signal to noise level. In these measurements the gate was typically set to 50ns to make sure that all the signal from a single bunch was captured with the current 50ns spacing used for protons physics. Figures 1 and 2 show the typical evolution of the schottky signals along the LHC cycle for ions and protons respectively. It can be seen that with ions the transverse schottky sidebands are clearly visible in the spectra at injection, up the ramp and during the entire stable beams period. This allows for a continual measurement of both tune and chromaticity throughout the entire fill. For protons, however, the transverse schottky sidebands disappear during the ramp and only re-appear several tens of minutes into the stable beams period. The reason for this is linked to the controlled longitudinal blow-up performed on the beam during the ramp to maintain a constant bunch length. It is then thought that the bunches continue to oscillate longitudinally for quite some time after this longitudinal blow-up is switched off at top energy, before quietening down when the transverse sidebands once again appear.

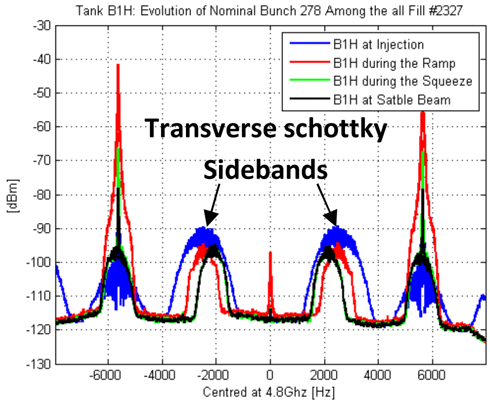

Figure 1: Evolution of the schottky signal for a nominal Pb^{82+} bunch (9x10^9 charges) along fill #2327.

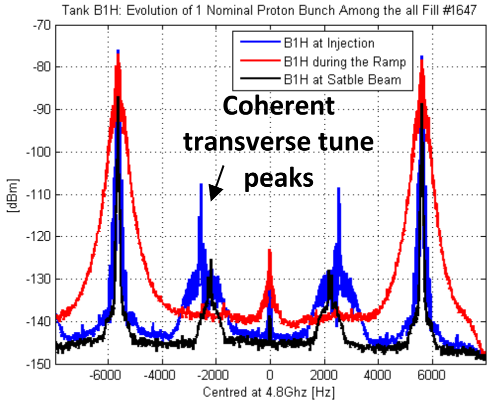

Figure 2: Evolution of the schottky signal for nominal proton bunch (1.2x10^{11} charges) along fill #1647. In red the schottky spectra during the ramp during which the transverse schottky sidebands are no longer visible.

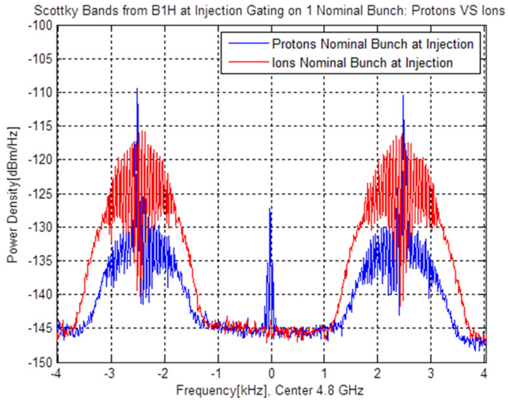

Figure 3: Schottky signal comparison at injection between a nominal ion bunch (red) and a nominal proton bunch (blue).

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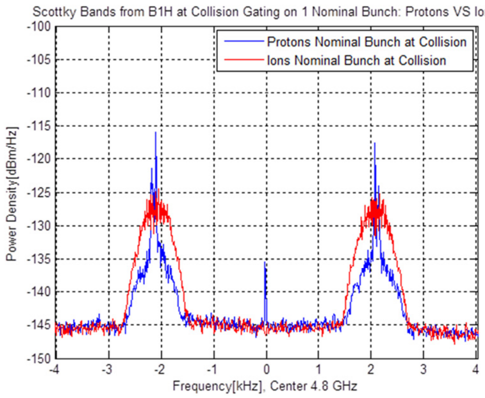

Figure 4: Schottky signal comparison at stable beam between a nominal ion bunch (red) and a nominal proton bunch (blue).

A comparison of the transverse schottky sidebands at injection and stable beams is presented in Figures 3 and 4. These were obtained by averaging the continuous 4096 point FFT spectra calculated from the 44 kHz sampled data over 29 seconds. Compared to protons with Q = 1, the ion signal is expected to deliver Q times the power for the same number of charges in the ring ($Q\mathrm{x}N_{IONS} = N_{PROTONS}$). This is 19 dB stronger for lead ions with Q = 82. Even though the proton intensity is some 13 times higher than the lead ion intensity, the ion signal therefore remains some 8dB larger than the proton signal at all moments of the fill. This, combined with the absence of controlled longitudinal blow-up for ions, significantly improves the conditions for fitting the spectrum, allowing the beam parameters to be computed for ions throughout the cycle.

TUNE AND CHROMATICITY MEASUREMNTS

Tune Measurements

The tune corresponds to the average position of the centre of both schottky bands with respect to the revolution frequency. Once the schottky spectra are visible the tune can therefore be computed by a suitable fitting of the two sidebands [5]. An example of the evolution of the tune from a nominal ion bunch during the LHC fill is shown in Figure 5.

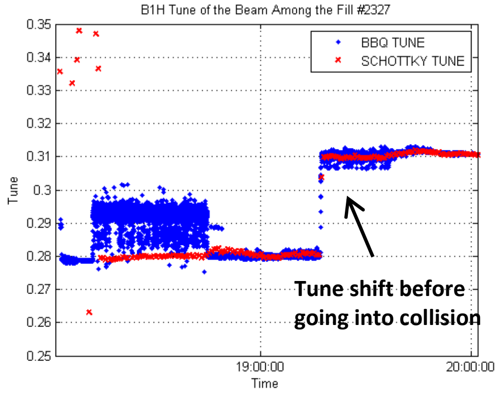

Figure 5: Tune evolution for a nominal ion bunch along fill #2327.

The tune derived from the schottky spectrum with ions (red trace in Fig. 5) is seen to give reproducible results from injection right into physics. This can be compared to the regular LHC tune measurement, based on the Base Band Tune (BBQ) detection technique [6], shown as the blue trace in Fig. 5. Detecting the coherent tune, the BBQ system suffers from considerable interference due to the use of a transverse feedback system to stabilise the beams throughout the injection, ramp and beta squeeze sequence. It is also optimised for high intensity proton bunches; leaving it with signal to noise issues for the much lower intensity ion bunches. However, since it takes a minimum of ~20 seconds of averaging for the schottky system to produce a new, useable spectrum, compared to the 12.5 Hz update rate of the BBQ, the schottky results are too slow to be used as an input for the tune feedback system.

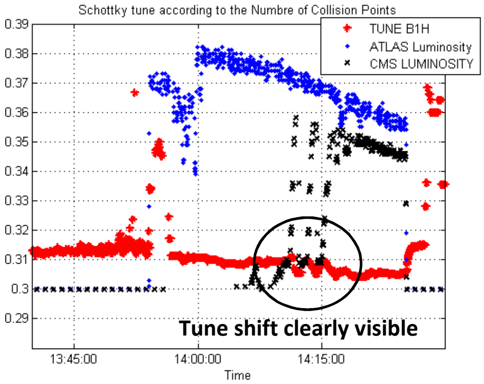

Figure 6: Single bunch tune shift measured using the schottky system during a head-on beam-beam study in the LHC.

Due to the fact that the LHC transverse schottky system is currently the only system able to measure individual bunch tunes, it is heavily used during LHC machine development periods. Figure 6 shows the results from one such study, where the tune shifts caused by head-on beam-beam were being investigated. In this case proton bunches are first brought into collision in the ATLAS experiment (collision rate shown by the blue curve) before being made to collide in the CMS experiment (collision rate shown by the black curve). The tune of the bunch is clearly seen to change as it experiences the beam-beam force from one or two experiments and also follows the repeated collide and non-collide status of the CMS experiment. The tune shifts measured in this way with the schottky system are in good agreement with the expected values, confirming the accuracy of the single bunch schottky tune measurements.

Chromaticity Measurements

Some attempts to compute the chromaticity from the schottky sidebands was made for lead ion spectra. This involves fitting the two sidebands and extracting their widths. The chromaticity is then proportional to the difference in these widths. It is currently not possible to measure chromaticity with any other technique with physics production beams, which is why such a measurement using schottky signals is currently being pursued.

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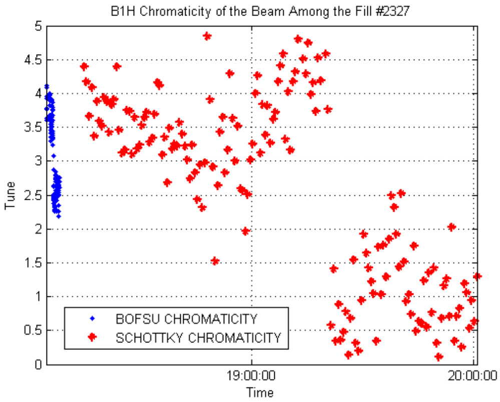


Figure 7: Chromaticity evolution for a nominal ion bunch along fill #2327.

An example of such results is shown in Figure 7. The standard chromaticity measurement (BOFSU Chromaticity), using frequency modulation and coherent tune measurement with the BBQ system, can only be performed at the start of the injection process when there is little intensity in the machine. An accurate comparison of the two measurements is therefore not possible.

It can be seen that there is considerable scatter in the measured schottky values, which results from the fact that there is little difference in the measured widths. This is a result of the high detection frequency (4.8 GHz) used by the pick-up, where the majority of the width comes from the energy spread in the beam, which is common to both sidebands. The contribution of chromaticity, which is asymmetric for the two sidebands, represents less than 1% of the total width at this frequency. Nevertheless, improvements to the fitting routines are currently being investigated, as a proven method of continuous chromaticity measurement would be of benefit to regular LHC operation.

THE SIGNAL PROCESSING CHAIN

Of the fours installed schottky systems (one per plane per beam), only the beam 1 horizontal system has been shown to give good signals with proton beams. It is suspected that one reason for this could be due to saturation of the electronics in the other channels by the strong coherent lines that are still present in the beam spectrum even at this high detection frequency, (see Fig. 2). These coherent lines can be over 50 dB higher than the schottky signals of interest and their suppression depends strongly on a good phase and amplitude match between the opposing waveguides in the pick-up.

Changes to the processing chain have therefore been made in order to try and reduce the influence of these lines. The original system uses a gate after a 100 MHz band pass filter and a 38 dB front-end amplifier to both select the bunch being measured and improve the signal to noise by cutting out the amplifier noise when there is no bunch present. However, this large bandwidth, required for the bunch by bunch measurement, means that the front-end amplifier has to deal with relatively large signals. The new scheme tested involves adding a second gate, this time right after the difference hybrid, whose sole job is to select the signal from the bunch of interest (see Fig. 10). Once selected this signal can be filtered to a much narrower bandwidth (in this case 24 MHz) before being amplified. The second gate is still present to cut out the front-end amplifier noise when there is no signal present.

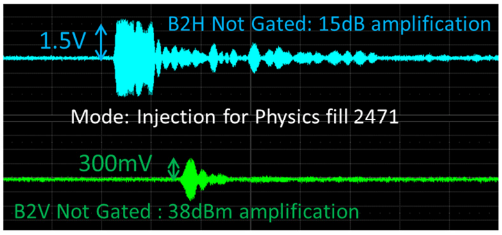


Figure 8: Oscilloscope measurement with protons at injection. View of the signal at the pick-up plate output. Blue trace has 15 dB amplification and no filtering, while green trace has 100 MHz band pass filter and 38 dB amplification.

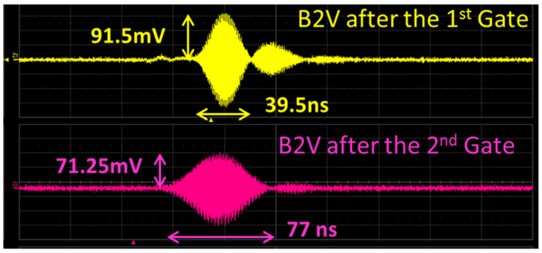
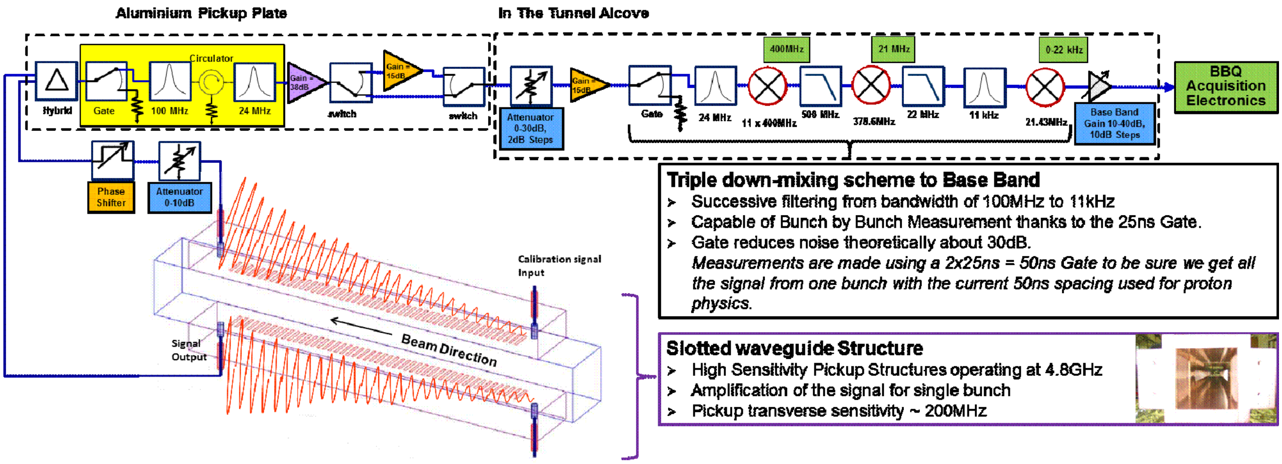


Figure 9: Oscilloscope measurement with protons at injection on the modified channel. Yellow trace shows the signal at the pick-up output with cascaded 100 MHz and 24MHz band pass filters and 38 dB amplification. Pink trace is taken after the second gate with further filtering by 24MHz band pass filters and 38 dB amplification.

The effectiveness of this approach was measured using a fast oscilloscope (18 GHz bandwidth, 60 GS/s) installed in the gallery next to the LHC tunnel. In this way it was possible to observe the time domain signals coming from the pick-up plate after they had gone through the difference hybrid, band pass filter and 38dB front-end amplifier. Comparing the green trace of Figure 8 with the yellow trace of Figure 9, it can be seen that the output voltage (and hence input) of the front-end amplifier is reduced by more than a factor of 3, corresponding to the reduction in input bandwidth. This is sufficient to remain well below the 1dB compression point of this amplifier under all conditions.

Despite these modifications (see Fig. 10) the overall signal to noise did not improve significantly on the channels where this change was implemented. Further investigations have raised the possibility that structural defects in the pick-up, and in particular in the phase matching between waveguides could be the reason for the reduced performance of three of the installed systems.



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 with the current 50ns spacing used for proton physics.

Slotted waveguide Structure

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

Figure 10: Analogue Processing Chain describing the modified pickup plate with the addition of a gate and a 24 MHz filter (elements unlighted in yellow).

CONCLUSION

The LHC 4.8 GHz travelling wave schottky system has been shown to give good results with lead ion beams, but is proving more problematic with high intensity proton beams. Measurements during proton physics energy ramps are not currently possible due to the controlled longitudinal blow-up performed on the beam to maintain the bunch length constant.

Analysis of the schottky tank output signals indicate that the poorer signals observed on 3 of the schottky measurement chains probably originate from the tanks themselves and not the analogue electronic chains. Investigations are now underway to pinpoint this source with a view to significantly improving the system for the LHC run at 6.5 TeV in 2014.

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