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# Bunched-beam Schottky monitoring in the LHC

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ABSTRACT

The LHC Schottky beam diagnostic system has the potential to measure beam parameters such as tune, chromaticity and momentum spread in a non-invasive way. It does so by detecting beam induced signals at 4.8 GHz, and extracting the characteristic modulation caused by incoherent motion of particles within a bunch. The system was commissioned in 2011 and provided satisfactory beam-parameter measurements during LHC Run I for lead-ions. However, for protons its usability was substantially limited due to strong interfering common-mode signals. The system was upgraded with optimized traveling-wave pick-ups and an improved microwave signal path. Design and operational aspects for the complete system are shown, and the results from measurements with LHC beams in Run II are presented and discussed.


## 1. Introduction

'Shot noise' was discovered in 1918 by W. Schottky during his experiments with vacuum tube audio amplifiers. While studying fluctuations in the tubes anode current, he discovered that with enough gain it was possible to distinguish the impulses from individual electrons arriving at the anode. He named this effect "shot noise" after the crackling sound he heard in his headphones. He later showed that the effect originates from the statistical fluctuation of current due to being made up of individual packets of finite charge [1].

In 1971 the same phenomenon was observed with proton beams in the Intersecting Storage Ring (ISR) at CERN [2]. It was discovered that the complex particle motion imprints valuable information about the state of beam and machine into the noise. This makes "Schottky signals" an important non-invasive diagnostic tool, in particular for storage rings.

Additionally, Schottky signals are also the foundation for stochastic cooling, a concept first published by Simon van der Meer in 1972 [3]. Schottky diagnostics and stochastic cooling techniques became essential for every-day operation of accumulator rings, allowing many injections of long, low intensity bunches to be collected into a dense 'stack' of particles. Good examples are the $\bar{p}$ accumulation schemes at CERN (ISR, SPS, AA, AC, AD, ELENA), Fermilab (Accumulator and Debuncher for $p\bar{p}$ collisions in the Tevatron), and BNL (RHIC).

Yet, using Schottky signals for the monitoring of bunched proton or antiproton beams with short, typically non-Gaussian particle distributions has turned out to be very challenging. A strong unwanted common mode signal content unexpectedly persists even at frequencies well above the first order high frequency cut-off of the beam spectrum. This typically leads to saturated amplifiers in the RF electronics and distortion problems. That is why attempts at bunched beam stochastic cooling have failed, both, in the SPS $p\bar{p}$ program at CERN (1990), and also in the Tevatron at Fermilab [2]. A successful cooling of bunched gold ions has been achieved at RHIC (BNL) in 2000 [4]. RHIC was profiting from the fact that the Schottky signal power for ion beams scales quadratically with the ionic charge number $z$. Therefore, gold ions with $z = 79$ provide almost 40 dB more signal power than a beam consisting of the same number of proton or antiprotons ($z = 1$).

The Large Hadron Collider (LHC) at CERN has been equipped with a 4.8 GHz transverse Schottky system for beam diagnostics purposes, which was commissioned in 2011 as part of the U.S. LHC Accelerator Research Program (LARP). The LHC collides proton or lead-ion ($Pb^{82+}$) beams at a center-of-mass energy of up to 7+7 TeV.

The LHCs 400 MHz main RF frequency results in a 1 ns four-sigma bunch length and an intensity of $\approx 10^{11}$ protons [5]. These short, high intensity bunches cause strong coherent signal components in the Schottky spectrum, which can be up to 100 dB larger than those of the incoherent signals to be measured. The dynamic range requirements therefore pose a major challenge for bunched beam Schottky diagnostics in the LHC.

During LHC Run I (2010–2013) the practical usability of the LHC Schottky system was limited to lead ion beams, where the common-mode signals at the pick-up operational frequency are weaker (longer

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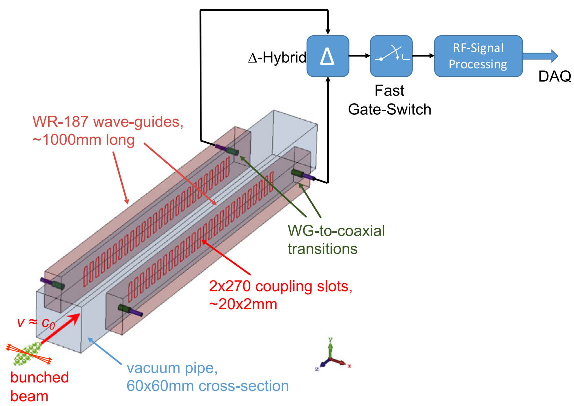


**Fig. 1.** High-level overview of the LHC Schottky pickup and signal processing components.

bunches), and the power in the incoherent signals gain with the square of the higher charge state ($z = 82$). A major overhaul of the Schottky beam pickups during the long shutdown 1 (LS1: 2013–2014), complemented by a redesign of the RF front-end signal processing finally enabled a reliable and reproducible detection of Schottky signals for bunched proton beams.

There are two important use-cases in which this system can support the everyday physics operation: One is the non-perturbative measurement of the machine chromaticity, the other is the measurement of the betatron tune. Chromaticity in the LHC is typically measured by modulating the RF frequency while observing the change in tune. However, for various reasons this technique is limited to low intensity beams, implying that chromaticity cannot be measured during physics production runs with high intensity beams [6]. The standard tune measurement system also suffers when the machine is filled up with high intensity bunches. While this system has a high sensitivity [7] its operational frequency overlaps with the transverse stability feedback system of the LHC, again, limiting the measurement capabilities for high intensity physics production beams. This limits the tune measurement to a small number of 'probe bunches', for which the transverse feedback is disabled. A reliable Schottky measurement system should overcome these issues while in addition providing a rich picture of the internal dynamics of the transverse beam motion of particles within a bunch, which should lead to a better understanding of the machine.

This report starts with a high level overview of the LHC Schottky system, followed by a brief review of bunched beam Schottky theory (Section 2). A detailed look is then taken at the components which have been upgraded since 2013. This includes the overhaul of the beam pickups, the redesigned and optimized RF front-end, now equipped with new filters, and an analysis of the overall noise performance including the down-converter chain in the RF back-end. Several new algorithms, to process the acquired spectra and extract parameters such as tune and chromaticity are also discussed, along with their performance evaluated during dedicated machine development (MD) periods.

### 1.1. System overview

The LHC Schottky system consists of four identical channels, for the horizontal and vertical plane of each of the counter-rotating LHC beams. A schematic overview of the main components of one channel is shown in Fig. 1.

The Schottky beam pickup (Section 3) consists of two symmetrically arranged, slot-coupled waveguides operating at 4.8 GHz, coupling to the beams coherent and incoherent signal contributions. Subtracting both output signals by means of a difference ($\Delta$) hybrid reduces the large common mode ($\Sigma$) signal contributions, i.e. most of the unwanted coherent spectral components derived from the bunch intensity, enabling the detection of transverse low-level signals. A fast gate-switch (Section 4.2) allows to select one or more bunches and is followed by a narrow-band signal processing system, optimized for low-noise and high dynamic range. In practice, the RF signal processing is divided in two parts. A 4.8 GHz 'front-end' gating and gain section (Section 4.3), which is mounted directly on top of the Schottky beam pickup, and a 'back-end' down-converter section (Section 5), located in a nearby underground alcove. Both RF sections are interconnected via ≈20 m long, high quality coaxial cables. After down-conversion in three stages, the resulting Intermediate Frequency (IF) signal represents a 15 kHz wide slice of the input spectrum centered around ≈4.8 GHz. A spectral analysis of this digitized signal reveals the 'Schottky sidebands' with their characteristic features, which are further processed by real-time data extraction algorithms (Section 6) to measure beam and machine parameters such as synchrotron and betatron tunes, chromaticity or momentum spread.

## 2. Theoretical background

As shown in Fig. 2, Schottky signals can be separated into spectral components derived from both, the longitudinal and transverse motion of particles. Even though the LHC Schottky pickups have been designed to detect the fluctuations of the charge density in the transverse plane, they also have a residual sensitivity to longitudinal fluctuations, which explains why both components are visible in the measurement.

These can be further subdivided into a coherent part, which corresponds to the collective motion of the whole bunch and an incoherent part, which corresponds to the random movement of individual particles within the bunch. Qualitatively, the former results in strong sharp, well-defined peaks at characteristic frequencies in the spectrum, such as the revolution frequency $f_{\mathrm{rev}}$ or betatron frequency $f_\beta$, while the latter results in an array of lines merging into wide humps of lower amplitude around these peaks.

Extracting a beam parameter of interest requires an analysis of the measured Schottky spectra. See e.g. [8–11]. The essentials are summarized as follows:

The chromaticity, $Q'$, is defined as the change in betatron tune $Q = Q_{int} + q$ (with $Q_{int}$ and $q$ being the integer and fractional tune respectively) for a relative change in momentum $\Delta p/p$ of the beam or an individual particle:

$$Q' = Q\xi = \frac{\Delta q}{\Delta p/p} \tag{1}$$

with $\xi = Q'/Q$ being the relative chromaticity. In practice, with many particles in the beam there is always a momentum spread $\Delta p/p$ present, which causes tune spread $\Delta Q = Q' \cdot \Delta p/p$. The 'classical' method to measure the chromaticity utilizes the fact that a change of the RF frequency changes the beam momentum, which leads to a change of the relative revolution frequency $\Delta f/f$ and therefore a change of the betatron tune proportionally to the given chromaticity:

$$\frac{\Delta Q}{Q} = \xi \frac{1}{\eta} \frac{\Delta f}{f} \tag{2}$$

with the slip factor $\eta = 1/\gamma^2 - \alpha$. For the LHC, the momentum compaction factor $\alpha = 1/\gamma_{\mathrm{tr}}^2$ is given by gamma transition $\gamma_{\mathrm{tr}} = 55.68$. The slip factor $\eta$ relates a change of the relative momentum $\Delta p/p$ to a change of the relative frequency $\Delta f/f$:

$$\eta = \frac{\Delta f/f}{\Delta p/p} \tag{3}$$

where the frequency $f$ can be the revolution frequency $f_{\mathrm{rev}}$ or the RF frequency $f_{\mathrm{RF}}$.

Due to the periodic nature of the bunch passage, the frequency domain representation of Schottky signals consists of an infinite series of revolution harmonics, at integer multiples of the revolution frequency ($nf_{\mathrm{rev}} = n \cdot 11.245$ kHz). The incoherent motion of the particles is reflected in the bunched-beam spectrum as noise 'humps', created by a multitude of lines separated by the synchrotron frequency. The