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EXPERIMENTAL AND SIMULATED LHC SCHOTTKY SPECTRA

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Abstract

Schottky monitors are valuable non-invasive tools used for beam diagnostics, providing insights into crucial bunch characteristics such as tune, chromaticity, bunch profile, or synchrotron frequency distribution. This study investigates Schottky spectra at the Large Hadron Collider (LHC) through a combination of simulations and measurements. Experimental data from lead ion bunches are compared with simulated spectra derived from time-domain, macro-particle simulations. In particular, amplitude detuning due to the octupole magnets, known to influence the Schottky spectra, is incorporated into the simulations. These simulations are performed for various octupoles currents with the goal of better understanding the interplay between octupoles and the Schottky spectrum. Finally, measured spectra are compared to simulations performed using the best available knowledge of the parameters impacting the spectra.

INTRODUCTION

The characterisation of beam properties in accelerators is crucial for optimising their performance and ensuring safe operation. One of the diagnostic tools used for this purpose is the Schottky monitor, which provides insights into various beam parameters such as tune, chromaticity, and bunch profile. In the LHC, octupole magnets play a significant role in beam dynamics, primarily by introducing amplitude-dependent tune shifts causing modifications in the Schottky spectra. While this alteration may initially seem challenging for parameter extraction from the Schottky spectrum, it also presents potential benefits. Specifically, octupoles have been observed to reduce the coherent components in the spectrum. This reduction can be highly beneficial, especially considering that existing theories for parameter extraction only focus on non-coherent spectra [1, 2].

The following section presents the experimental measurements and recalls some theoretical aspects of the effects of octupoles before providing a comparison between simulated and measured spectra for various octupole currents. Finally, a benchmark of the theoretical approach from Ref. [3] against the experimental Schottky spectra is also presented.

EXPERIMENTAL AND SIMULATED SCHOTTKY SPECTRA

Effect of the Octupoles

For a given particle, octupoles induce a transverse, action-dependent tune shift, which at the leading order of the octupole current is characterised by [4]

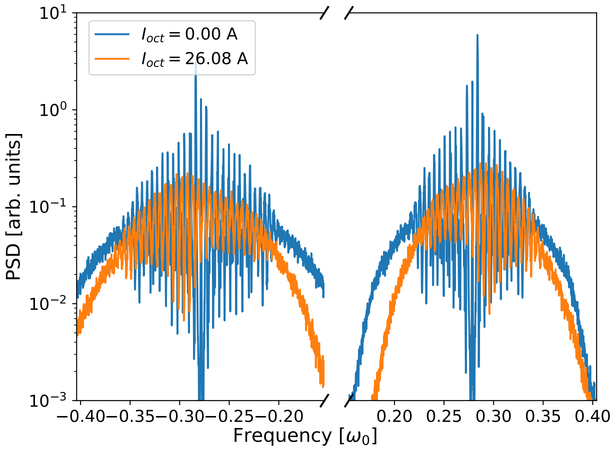

Figure 1: Experimental transverse horizontal Schottky spectrum for two values of octupoles current.

$$\begin{cases} Q_x & = Q_{x,0} + \alpha_x J_x + \alpha_{xy} J_y \\ Q_y & = Q_{y,0} + \alpha_y J_y + \alpha_{xy} J_x \end{cases},$$

where $Q_{x,0}, Q_{y,0}$ are the nominal tunes, J_x, J_y the transverse action variables, and $\alpha_x, \alpha_y, \alpha_{xy}$ the detuning coefficients. The values of the detuning coefficients are calculated based on the machine optics and the octupole currents I_{oct}, as discussed in Ref. [5].

The impact of the octupoles on Schottky spectra is illustrated in Fig. 1, which shows two experimental spectra, with and without the influence of octupoles. Notably, the satellite peaks are smeared due to the octupolar field, resulting in reduced peak heights. In particular, the heights of the coherent peaks are significantly reduced compared to the case without octupoles.

In addition, octupoles also influence the shape, the width, and the centre of mass of the side-band spectra, and this has to be considered for parameter extraction. Assuming Gaussian transverse bunch profiles, the tune shift of the individual particles translates in the horizontal Schottky spectrum as a centre of mass shift, given as a function of the transverse emittances ϵ_x and ϵ_y, by [3]

$$\mu_\pm = \mu_{\pm,0} \pm \omega_0 (2\alpha_x \epsilon_x + \alpha_{xy} \epsilon_y), \tag{1}$$

where $\mu_{\pm,0} = \omega_0 (n \pm Q_{x,0})$ denotes the original centres of mass of the sidebands in the absence of an octupolar field, and ω_0 is the revolution angular frequency, with the Schottky spectrum taken at its n^{th} harmonic.

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Simulation Parameters

To accurately replicate the experimental spectra with macro-particle simulations, a detailed knowledge of machine and beam parameters is required. Parameters like transverse and longitudinal tunes need to be precisely known to closely match the simulation with the measured spectra. The simulated spectra will be benchmarked against experimental measurements taken during the dedicated Machine Developement session (MD) 9263.

The horizontal position of the Bessel satellites for a given particle is defined by $Q_x + pQ_s$ [1], where p is the satellite order and Q_s is the synchrotron tune. Hence, precise knowledge of the synchrotron tune is essential for good alignment between simulation and measurement, especially for high-order satellites. The synchrotron frequency can theoretically be obtained from the measurement of the radio-frequency (RF) voltage. However, there can be discrepancies between the measured voltage and the voltage experienced by the particles. Given that the measured RF voltage's precision might not be adequate for a good spectral overlap, we fit the nominal synchrotron frequency (or equivalently, the RF voltage) to the measured Schottky spectra. As the RF voltage remained constant across our MD measurements, a single spectra fit was performed, and the same RF voltage was applied to all simulations.

The transverse tunes are obtained from the LHC Base-Band Tune (BBQ) system [6]. As this instrument measures the tune of the particles that are affected by the octupolar field, the shift caused by the latter has to be substracted in order to obtain the nominal tune. This is conducted following a similar approach as Eq. (1) and the nominal tune is obtained with

$$\begin{cases} Q_{x,0} &= Q_{x,BBQ} - 2\alpha_x\epsilon_x - \alpha_{xy}\epsilon_y \\ Q_{y,0} &= Q_{y,BBQ} - 2\alpha_y\epsilon_y - \alpha_{xy}\epsilon_x \end{cases}.$$

The longitudinal bunch profile was assumed to be Gaussian for the macro-particle simulation. The standard deviation σ_t was obtained with a Gaussian fitting of the bunch profile obtained from the wall current monitor.

As emittance measurements with the wire scanner were only performed a few times during the MD, the emittances used for the simulations were derived from the experimental spectra. The total power of the latter being proportional to the emittance [3]. The other parameters in Tables 1 and 2 come from direct measurements or machine design.

Simulation Benchmark

Figure 2 illustrates the comparison between simulated and experimental spectra for two octupole current values, focusing on the lower sidebands of both horizontal and vertical

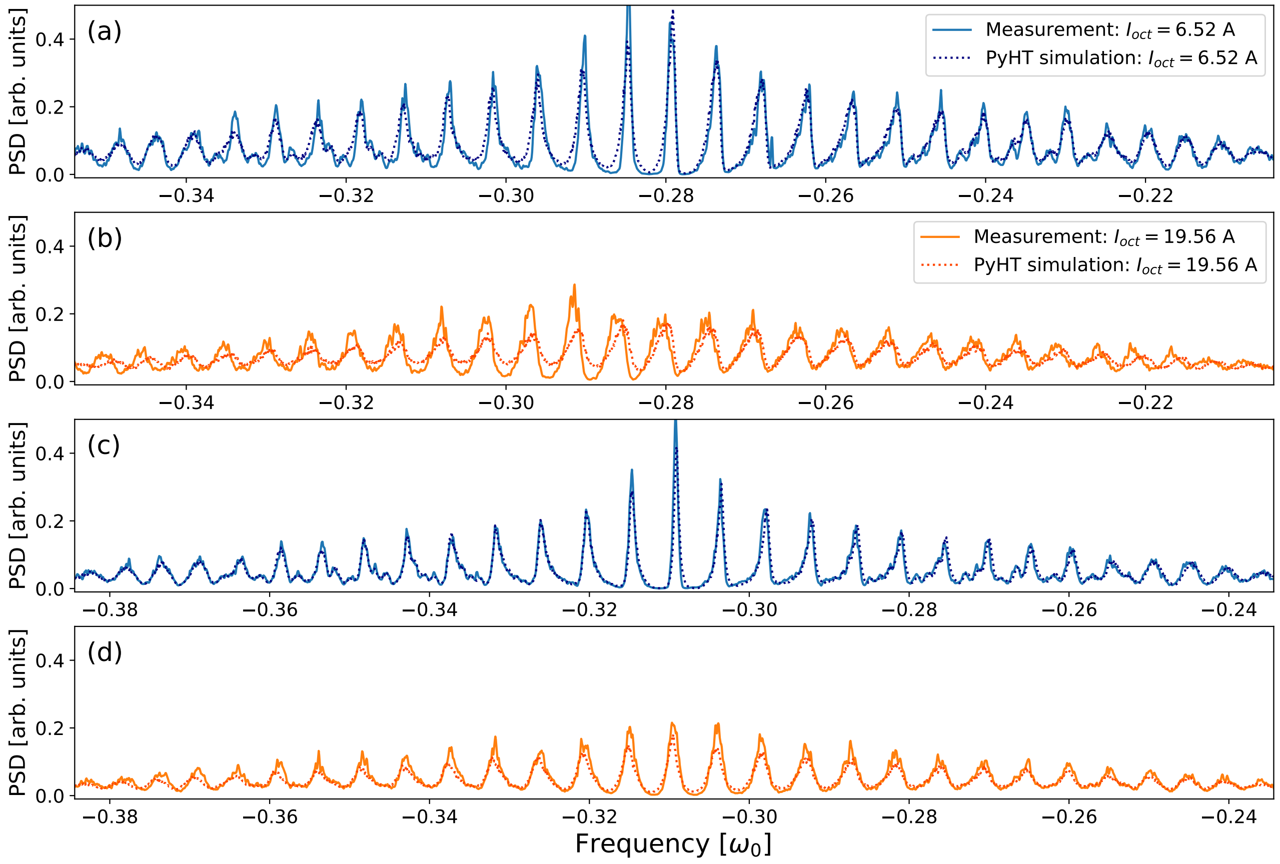

Figure 2: Comparison of measured (solid lines) and simulated (dotted lines) Schottky spectra focusing on the lower horizontal (a, b) and lower vertical (c, d) sidebands for two octupole currents.

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Table 1: Common PyHEADTAIL Simulation Parameters

LHC circumference	26.659 km
Energy per ion	36.9 TeV
Ion charge	82 e
Ion mass	193.687 GeV/c^2
Slippage factor	3.2×10^{-4}
RF harmonic	35640
RF voltage	8.12 MV
Number of macroparticles	100 000
Number of turns	10 000
Number of averaged spectra	500

Table 2: Simulation-specific PyHEADTAIL Parameters

I_{oct} [A]	6.52	19.56
α_x [A^{-1}]	5.07×10^4	1.52×10^5
α_y [A^{-1}]	5.29×10^4	1.59×10^5
α_{xy} [A^{-1}]	-3.61×10^4	-1.08×10^5
N [ions per bunch]	8.65×10^7	9.36×10^7
ϵ_x [µm]	1.62	1.33
ϵ_y [µm]	0.68	0.57
$Q_{x,0}$	64.2788	64.2790
$Q_{y,0}$	59.3090	59.3094
Q'_x	15	15
Q'_y	15	15
σ_t [ns]	0.41	0.36

planes. The macro-particle simulations have been performed with PyHEADTAIL [7, 8], using the method presented in Ref. [9] to compute the Schottky spectra. The agreement is excellent in the vertical plane for both values of octupole current, and in the horizontal plane for the lowest octupole current. A discrepancy appears in the horizontal plane for the highest octupole current, that could be attributed to an overestimation of the horizontal emittance. As previously mentioned, the emittances were measured only sporadically with the wire scanner, and the relative changes in emittance were inferred from the Schottky spectra themselves.

We can further note from Fig. 2 that the octupoles' influence is more pronounced in the horizontal plane, even with identical octupole current settings. This observation aligns with Eq. (1), where the main contribution to the tune shift comes from the term $2\alpha_i \epsilon_i$ (with i denoting the plane x or y), which is proportional to the emittance of the concerned plane. Given the smaller vertical emittance as shown in Table 2 and the higher value of the direct detuning α_x (or α_y) vs. the cross detuning α_{xy}, the octupole effect is indeed larger in the horizontal plane.

Theoretical Benchmark

Figure 3 compares the theoretical vertical Schottky spectrum, accounting for octupole effects as derived in Ref. [3], with the experimental measurement and simulated spectrum for the conditions described in Tables 1 and 2. Consistent with previous simulations, good agreement is obtained in the vertical plane. The analytical formula capable of predicting spectra in the presence of an octupolar field offers the advantage of being significantly faster than the time-consuming macro-particle simulations, potentially allowing real-time fitting of spectra for parameter extraction.

CONCLUSION

In this study, we investigated the Schottky spectra at the LHC through a combination of experimental measurements and simulations. Our findings highlight the significant influence of octupole magnets on the Schottky spectra. By comparing experimental data with simulations, we outlined the intricate relationship between the amplitude detuning from octupoles and Schottky spectra. Despite the challenges posed by such detuning, they also offer benefits by reducing coherent components in the spectrum, which is beneficial for parameter extraction. Our simulations demonstrated very good agreement with experimental data when using accurate parameter estimations. This validates our simulation methods and underscores the importance of considering octupole-induced detuning when interpreting Schottky spectra.

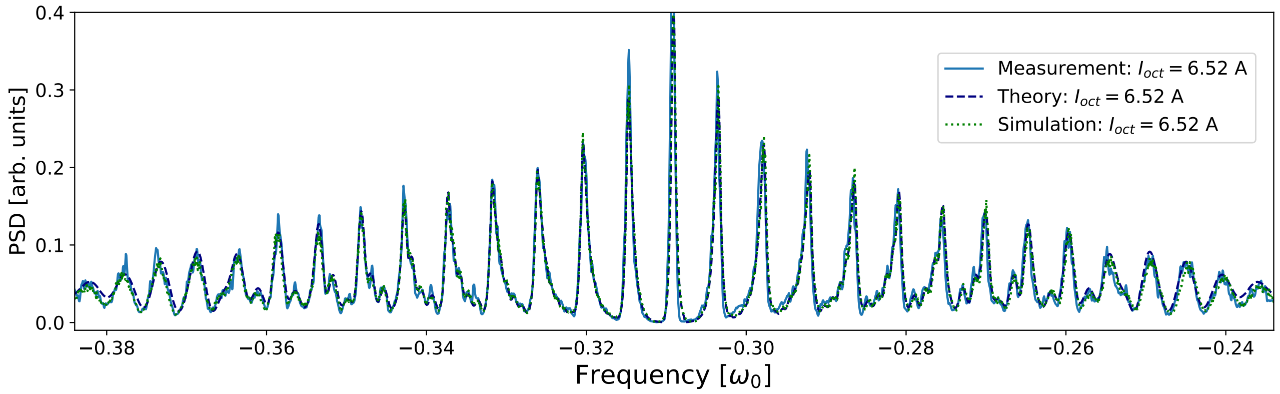

Figure 3: Comparison of experimental, theoretical, and simulated vertical Schottky spectra (lower sideband).

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