RF PHASE MODULATION STUDIES AT THE LNLS ELECTRON STORAGE RING

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Abstract

In this work we present a set of measurements of the effectiveness of RF phase modulation on the second harmonic of the RF frequency as a mechanism to damp longitudinal coupled-bunch instabilities. We also propose a theoretical model of the damping mechanism, in which the increase of the spread in synchrotron frequencies inside the bunches produced by phase modulation is responsible for damping the centroid dipolar coherent motion caused by an external excitation, which could be a Higher Order Mode (HOM) of the RF cavities driving the coupled bunch motion. We measured the coherent synchrotron oscillation damping of a single bunch under two circumstances, with and without phase modulation, and determined the amount of extra damping due to the modulation. With this experiment we could also measure the frequency of small oscillations around the stable islands formed by phase modulation and its behavior when the RF phase modulation amplitude and frequency are changed. We performed measurements of Beam Transfer Function (BTF) to observe the effects of phase modulation on the stable area for coherent oscillations and compared the results with our theoretical model.

INTRODUCTION

The LNLS Synchrotron Light Source is based on a 1.37 GeV electron storage ring with an initial current of 250 mA in routine user shifts. Due to the need to install insertion devices and store higher currents the RF system was upgraded with the installation of a second active cavity, which operates at a frequency of 476.066 MHz. This second RF cavity has a longitudinal Higher Order Mode (HOM) - with a frequency of 903 MHz - excited by the beam which causes an orbit horizontal distortion with an amplitude of $\pm$ 5 μm detectable at the most sensitive beam lines. This orbit distortion was intermittent and appeared when the beam coupled with the HOM of the cavity exciting a large longitudinal dipolar oscillation. With temperature and plunger scans we were able to identify the longitudinal mode L1 (associated with the CBM 133) of the new RF cavity as the main source of instabilities in the machine however we could not find a cavity operation condition where this HOM is damped. Since it was not possible to find a passive way to create a region that would be free from instabilities, an active solution in the form of phase modulation of the RF fields at twice the synchrotron frequency was attempted with success. The phase modulation has a noticeable impact on CBM amplitudes and helps alleviate the orbit fluctuation [1].

THEORY

We initially follow the standard hamiltonian analysis for the longitudinal dynamics with phase modulation. The time averaged hamiltonian [2] for an electron in a bunch subjected to phase modulation can be written as follows

$$\langle K\rangle_t = \left(\omega_s - \frac{\omega_m}{2}\right)\tilde{J} - \frac{\omega_s \tilde{J}^2}{16} + \frac{\omega_s \epsilon \tilde{J}}{4}\cos 2\tilde{\psi} \qquad (1)$$

where $\omega_s = 2\pi f_s$ is the synchrotron frequency, $\epsilon = A_m \tan\bar{\phi}_s$, $\bar{\phi}_s = \pi - \phi_s$ where ϕ_s is the synchrotron phase, A_m the modulation amplitude and ω_m the modulation frequency.

The effect of phase modulation is to create new regions of stability inside the bunch, besides the original one. As the formation of those islands depend on the amplitude of the modulation, there is a continuum of phase space forms from one island to the appearance of the three islands when $\omega_m \leq (2-\epsilon/2)\omega_s$ and the formation of only two islands when $\omega_m > (2-\epsilon/2)\omega_s$. The longitudinal phase space for the situation described above is shown in Figure 1.

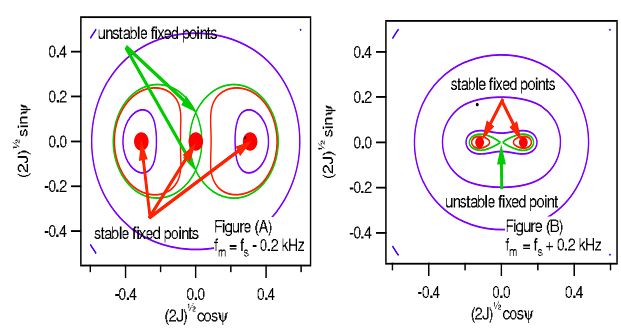

Figure 1: Longitudinal phase space for two different modulation frequencies.

Dynamics of small amplitude oscillations around the fixed points

The island frequency, as the synchrotron one is an important quantity since it describes the frequency of coherent oscillation of the particles inside the island when subjected to a longitudinal kick. It is possible to calculate the frequency of particle oscillations near the stable fixed points by expanding the Hamiltonian (1) in the neighborhood of these points. Using the following coordinates

$$\delta = -\sqrt{2J}\sin\psi + \sqrt{2J_0}\sin\psi_0 \qquad (2)$$

$$\phi = \sqrt{2J}\cos\psi - \sqrt{2J_0}\cos\psi_0 \qquad (3)$$

we find that

$$H' = \frac{A}{2}\delta^2 + \frac{B}{2}\phi^2 + \text{higher order terms} \qquad (4)$$

where the coefficients [3] A and B are functions of: ω_m, J_0, ψ_0 and ϵ.

The synchrotron tune is $\sqrt{AB}$ and is real for the stable fixe points and imaginary for the unstable ones. To find the phase space profile of the electron beam under phase modulation we must solve the Vlasov equation taking into account the radiation damping (γ_d) and quantum excitation($\kappa = \sigma_\delta^2 \gamma_d$). The solution of the Focker-Planck equation around each stable fixed point [4] is a gaussian in each coordinate

$$\Psi_0(\delta,\phi) = \frac{1}{2\pi\sigma_\delta\sigma_\phi} exp\left(-\frac{1}{2\sigma_\delta^2}\delta^2 - \frac{1}{2\sigma_\phi^2}\phi^2\right) \qquad (5)$$

with

$$\sigma_\delta = \sqrt{\frac{\kappa}{\gamma_d}} \qquad \text{e} \qquad \sigma_\phi = \sqrt{\frac{A}{B}}\,\sigma_\delta = \sqrt{\frac{A\kappa}{B\gamma_d}} \qquad (6)$$

If we go further in expanding (1) and use the canonical perturbation technique [5] it is possible to find the amplitude dependent island frequency that is given by

$$\omega(\hat{\phi}) \approx \omega\left(1 - \frac{3\,\omega_s}{16}\,\frac{A^2+B^2}{A^2|B|}\,\frac{\hat{\phi}}{8}\right), \qquad (7)$$

where $\hat{\phi}$ is the electron oscillation amplitude related to a stable fixed point.

Beam Transfer Function and Landau Damping

To explain why the modulation has such an intense effect on the amplitude of the instabilities, we propose a model in which the modulation creates a spread in the frequency distribution inside the bunch increasing the amount of Landau Damping. In this case we are only interested in the damping of synchrotron oscillations of the bunch centroid since the longitudinal instabilities come from a coupling between the synchrotron motion and a HOM of the RF cavity.

Considering that the particles in a bunch have a distribution $\Psi(\omega)$ of frequencies so that

$$\Psi(\omega) = N_c\Psi_{0c}(\omega) + N_i\Psi_{0i}(\omega) \qquad (8)$$

where the index c and i refer to the central and lateral islands respectively. The motion of the bean centroid can be written as

$$\bar{\tau}(\Omega) \propto N_c I_c(\Omega) + N_i\frac{\omega_c}{\omega_i}I_i(\Omega) \qquad (9)$$

where Ω is an external driving frequency and $I(\Omega)$ is the Longitudinal Beam Transfer Function (BTF) [6] which, for each island, can be defined as

$$I_{c,i}(\Omega) \equiv \pi\int_0^\infty \frac{r^2 dr}{\Omega - \omega_s(r)}\,\frac{\partial\Psi_{0c,0i}}{\partial r} \qquad (10)$$

where r is a local radial coordinate in the longitudinal phase space.

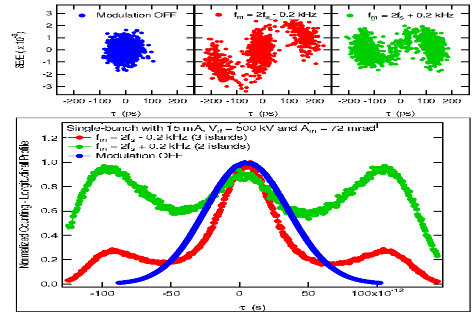

Figure 2: Single bunch simulation showing the phase space and the phase space projection in time domain for three different situations.

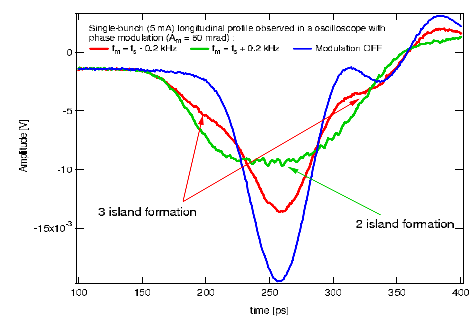

Figure 3: Beam profile observed in an oscilloscope.

EXPERIMENTAL RESULTS

We performed measurements in order to verify the results predicted by the theory outlined above.

Island Formation

Using a simulation code [7] we could calculate the longitudinal profile of the beam due to phase modulation. Comparing the results in Figures (2) and (3) and we observed that for frequencies $\omega_m < \omega_s(2-\epsilon/2)$ the profile corresponds to the case with three stable regions while when $\omega_m > \omega_s(2-\epsilon/2)$ only two stable regions are created.

Damping of Coherent Synchrotron Oscillations

Measurements of the synchrotron damping time were performed using a function generator and a phase shifter to created a longitudinal kick on the beam. Using the signal from a stripline the phase of the RF component of the beam was compared with the master RF signal. The damping time ratio for a single-bunch with phase modulation turned on and off is shown in Figure (4).

Island Tunes

An FFT of the damping time measurement data shows a low frequency sideband of the line corresponding to half of the modulation frequency. Analyzing the behavior of

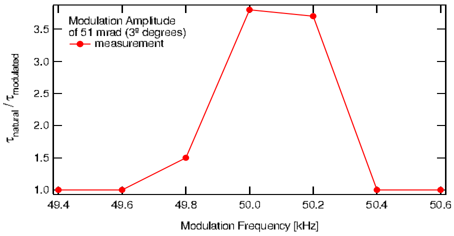

Figure 4: Increase in damping time as a function of modulation frequency.

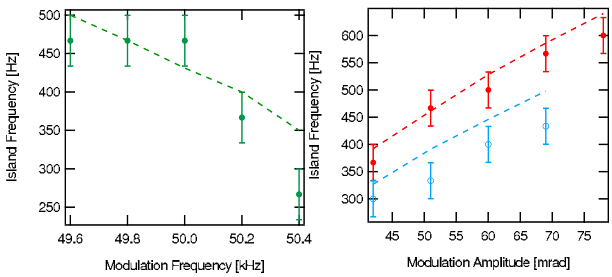

Figure 5: Island frequency as a function of modulation frequency and amplitude. The dots are experimental data and the curves theoretical results. The first graph (green) correspond to $A_m = 0.051$ rad and in the second graph the blue results correspond to $f_m = 50.2$ kHz and the red ones to $f_m = 49.8$ kHz.

this low frequency line we notice that it was related to the island tune. Figure (5) shows the dependence of the island frequency on modulation parameters and the corresponding theoretical values.

Longitudinal Beam Transfer Functions Measurements

Figures (6) and (7) show the results of measurements of the BTF for a single-bunch with 1 mA and also the results derived from theory. From the theory the only free parameter is the island population (N_c or N_i since $N_c + N_i = 1$) which was chosen so that the peaks in the amplitude response matched (Figure 7a). The theory agrees well with experimental results and reproduces some features which are important to understand the effect as the appearance of the peaks related to the frequencies of the central and lateral islands. The broadening of the amplitude response, if compared with the case without phase modulation, reflects the increase in frequency spread inside the bunch which is related to the extra amount of damping caused by RF phase modulation.

CONCLUSION

The results indicate that the mechanism responsible for damping CBMs instabilities is Landau Damping which is

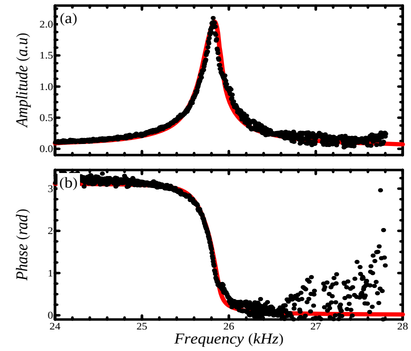

Figure 6: Beam transfer function for a single-bunch without phase modulation.

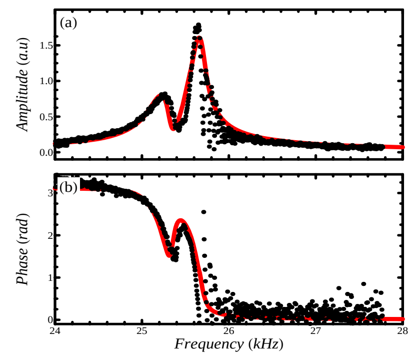

Figure 7: Beam transfer function for a single-bunch with phase modulation. The modulation parameters are: $A_m = 0.051$ mrad and $f_m = 51$ kHz, the island population is N_c=0.3 and N_i=0.7.

enhanced when using phase modulation due to the differences between the lateral and central islands frequencies.

ACKNOWLEDGMENTS

This work was supported by Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP).

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