RF PHASE MODULATION AT THE LNLS ELECTRON STORAGE RING

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Abstract

In the Brazilian Electron Storage Ring, we observed that modulating the phase of accelerating fields at twice the synchrotron frequency suppressed remarkably well a longitudinal coupled-bunch mode of the beam driven by one of the RadioFrequency (RF) cavities. We present results of a set of systematic measurements, in single and multi-bunch mode, aimed at characterizing the effects of the modulation on the beam. We also compare those experiments with the results of tracking simulations.

INTRODUCTION

The LNLS Synchrotron Light Source operates with a current of 250 mA in normal user shifts. However due to the need to install insertion devices and store higher currents, a second active cavity was installed at the end of 2003. This new cavity, which operates at a frequency of 476.066 MHz, has a longitudinal Higher Order Mode (HOM) - with a frequency of 903 MHz - excited by the beam which caused an orbit 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 which produces an orbit distortion that mimics the second order dispersion function [1].
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. Since it was not possible to find a passive way to create a region in the cavity spectrum 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 [5].

SIMULATION CODE

We developed a simulation code including beam loading effects and the presence of the longitudinal HOM associated with the fast orbit fluctuation at the Brazilian Light Source. The tracking code calculates the longitudinal bunch trajectories in the machine, considering the first 147 bunches as macroparticles and the last bunch with an internal structure. Using this scheme we were able to infer about the behavior of the bunches under phase modulation without a time consuming simulation.

The main idea behind this simulation tracking code is to give the possibility of observing the changes in the electron bunch distribution in phase space without the necessity of calculating the trajectories of many particles in all 148 bunches. This simulation has also a limitation, since one is forced to fill all the bunches with equal currents so as to be able to generalize the behavior observed for the bunch with internal structure to all others.

Equations of Motion

Table 1: LNLS main ring parameters.

Parameter	Symbol	Value
Beam Energy	E	1.37 GeV
Natural Energy Spread	σ_ϵ/E	5.4×10^{-4}
Circumference	C	93.252 m
RF frequency	f_{rf}	476.066 MHz
Harmonic number	h	148
Momentum compaction factor	α	8.3×10^{-4}
Radiation loss per turn	U_0	114 keV
Synchronous Phase*	ϕ_s	166.8^o

* Value calculated with V_{rf}=500 kV.

In order to calculate the trajectories of the macropaticles we used the following equations:

$$\tau_{b,n} = \tau_{b,n-1} - \alpha\delta_{b,n-1}T_0 \quad (1)$$

$$\delta_{b,n} = (1-2\lambda_{rad}T_0)\delta_{b,n-1} + \frac{(eV_{tot}-U_0)}{E}, \quad (2)$$

with

$$V_{tot} = V_{rf} + V_{bl} \quad (3)$$

where b is the index of the bunch and n the number of turns, T_0 the revolution period, V_{rf} the gap voltage and eV_{bl} the energy drained by the beam loading effect, which takes account of the beam loading of the fundamental mode and the longitudinal mode (L1). To simulate each particle in the last bunch we used the same equation as before and also considered radiation excitation.

The phase modulation was included in the calculation of the rf voltage as follows

$$V_{rf} = V_0 \sin(\phi_s - \omega_{rf}\tau_{b,n} + \phi_m \sin(\omega_m t)) \quad (4)$$

were V_0 is the peak voltage, ϕ_s the synchronous phase, ω_{rf} the angular rf frequency, ϕ_m the modulation amplitude

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and ω_m the modulation frequency which we set near the synchrotron second harmonic ($\omega_m = 2\omega_s + \epsilon$).

The beam loading effect was introduced in the tracking simulation using the following expressions [3]:

$$V_n = V_{n-1} e^{-\omega_{res}\Delta t/2Q_L + i\omega_{res}\Delta t} - k q_0 e^{-\omega_{res}^2 \sigma_\tau^2} \quad (5)$$

where ω_{res} is the angular frequency of the mode, k the loss factor, q_0 the charge per bunch and σ_τ the rms bunch length. A summary of the main parameters for the Brazilian machine is shown in Table[1].

Simulation Results

Using the tracking simulation code described above we were able to simulate the dipolar oscillation caused by the longitudinal HOM of the cavities. A comparison between two different tracking simulation shows that the change in the amplitude of the dipolar coherent synchrotron oscillation when the L1 mode is turned on is greater than 100 dB. Demonstrating the excitation of dipolar oscillation in the beam, as observed during users shifts.

In the tracking results it is also possible to observe the CMB excited by the HOM and Figure[1] shows the pattern of the bunch oscillation throughout the ring. We could also observe a good agreement between the value of the growth rate of the L1 mode give by the theory (38 ms) and simulation (45 ms).

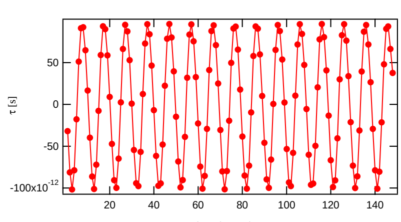

Figure 1: Phase relation between bunches caused by the presence of the longitudinal CBM 133.

MEASUREMENTS AND RESULTS

The characterization of the effects of phase modulation on the beam dynamics was made using both, single and multibunch mode. In single bunch we focused our attention on single particle dynamics due to a parametric resonance[4] excited by the modulation. The multibunch mode is the most important since it is where the most remarkable improvements takes place. However a systematic characterization in this mode is rather difficult due to large changes in the stored current during a frequency scan. In the following subsection we present a set of measurements done and a comparison with the simulation results.

Single-bunch Mode

The measurements were performed using an RF voltage 360 of kV[1], currents form 9 to 3 mA in a single-bunch and modulation amplitudes between 5 and 15 degrees. During each set of measurements we observed the amplitude of the synchrotron dipolar line, using an antena inside the new RF cavity, as we changed the modulation frequency from 41 to 43.5 kHz.

As predicted by the theory of parametric resonance, we observed an increase in the dipolar synchrotron line when we phase modulated the beam with frequencies close to twice the synchrotron frequency. Although there were no large changes in the width of the resonant window when we changed the modulation amplitude, the changing in behavior of the system for different currents was evident (Figure [2]). We noticed that for currents below 2 mA the dipolar line did not show up and as we decreased the current the resonant window also decreased. As predicted by the theory of parametric resonance, we expect to observe a different pattern between the scans were the modulation frequency were increased and decreased, but, to the contrary, the response of the dipolar line in both scans was exactly the same.

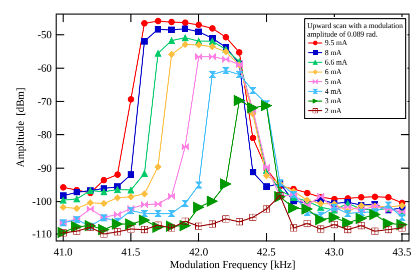

Figure 2: Example of measurement of the synchrotron line amplitude as a function of the stored current in a single-bunch.

Multibunch Mode

For the multibunch measurements we observed the amplitude of the synchrotron line at the RF harmonic 281, which was the frequency related the the L1 cavity mode, using a strip line.

The measurements in multibunch mode were slightly more complex than in single-bunch. Several scans were made with different values of stored total current and modulation amplitude. We observed that the response to the modulation was highly dependent on the modulation amplitude, with maximum reduction of the dipolar synchrotron line at 0.57 degree modulation amplitude and no substancial reduction of the same line with 0.86 degree of modulation amplitude as shown in Figure[3].

The frequency scans (at a fixed modulation amplitude) with different currents showed that the effect is current dependent and that the efficiency of the modulation to damp

[1]With this voltage the synchrotron frequency was 21 kHz.

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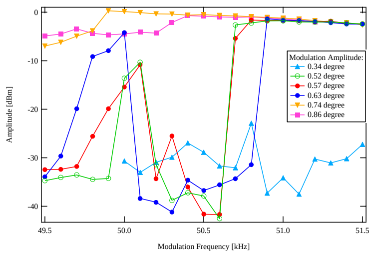

Figure 3: Behavior of the synchrotron line for different modulation amplitude in multibunch mode. Measurement done with 200 mA and gap voltage of 500 kV.

the dipolar synchrotron oscillation caused by a CBM decreased with decreasing current and completely vanished for currents bellow 100 mA. To overcome this dependence, during user shifts we constantly modulate the frequency at 400 Hz with an amplitude of 0.8 kHz.

Some results of our measurements are displayed in Figure[4] where we present upward frequency scans as a function of the stored current.

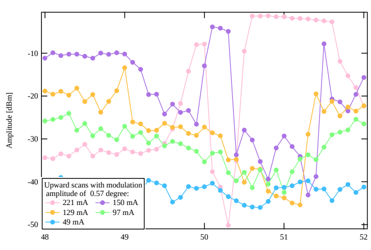

Figure 4: Frequency scans in multibunch mode as a function of stored current.

Comparison: Measurement vs Simulation

From the simulation in multibunch mode, we could observe a range of modulation frequencies for which the synchrotron line was damped (Figure[5]).This was true for a much wider range of modulation amplitudes (from 0.57 to 2.6 degrees) then the observed on the experiments (Figure[3]).

We also calculated the response of the synchrotron dipolar line with two different currents (Figure[6]), 200 and 100 mA, and the result agrees quite well with the measurements (Figure[4]).

CONCLUSION

We performed measurements in single-bunch and multibunch mode with the aim of characterizing the effect of the phase modulation of the RF accelerating field on the dynamics of the particles. In single-bunch mode we observed that, as predicted in the theory of para metric resonance, a dipolar oscillation is excited when we modulate with twice the synchrotron frequency. However there is a

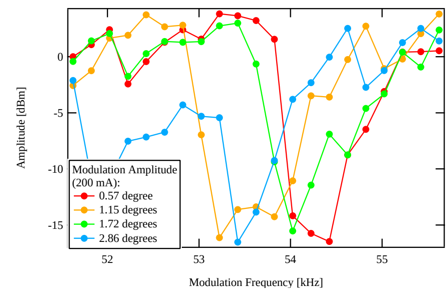

Figure 5: Simulation results of the amplitude of the excited dipolar oscillations in multibunch mode with different modulation amplitudes. The accelerating voltage was 500 kV and the current 200 mA.

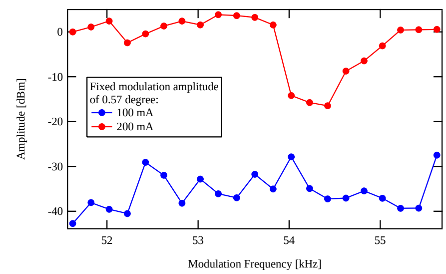

Figure 6: Simulation results of the amplitude of the excited dipolar oscillations in multibunch mode with two different values of stored. The accelerating voltage used was 500 kV.

great dependence of the resonance region with the stored current which can not be predicted by the linear theory. In multibunch mode we observed that the modulation could damp a large dipolar oscillation excited by a HOM and that the damping efficiency varies strongly with the stored current and the modulation amplitude. Comparing this results with those calculated using a simulation tracking code we could observe that it is capable to reproduce the measured effects indicating that the main ingredients responsible for the damping are taken into account in the simulation code. The next step is to find out which mechanism is the responsible to promote this damping and try to develop a simple theoretical model which describes the observed effects.

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