CONCEPTUAL DESIGN OF A 3RD HARMONIC CAVITY SYSTEM FOR THE LNLS ELECTRON STORAGE RING

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Abstract

The installation of a second RF cavity in the UVX electron storage ring at the Brazilian Synchrotron Light Laboratory (LNLS) at the end of 2003 brought about longitudinal instabilities driven by one of the HOMs of the new cavity. Even though the operational difficulties related to these unstable modes were successfully overcome by means of a combination of cavity tuning (using temperature and plunger adjustments) with phase modulation of the RF fields at the second harmonic of the synchrotron frequency, a more appropriate technique to avoid those problems is the use of higher harmonic cavities, which have the important advantage of providing damping of the longitudinal modes without increasing the energy spread. In this work we present the design of a passive higher harmonic cavity (HHC) system optimized for operation at the LNLS storage ring. The parameters for a set of cavities as well as the analysis of some of the effects that they may introduce in the beam dynamics are presented.

INTRODUCTION

The LNLS Synchrotron Light Source is based on a 1.37 GeV electron storage ring which operates with an inicial beam current of 250 mA in routine user shifts. The need to install insertion devices and plans to increase the initial stored beam current led to an upgrade of the RF system that was carried out in 2003. The installation of a second RF cavity had negative consequences with respect to the beam stability. A longitudinal Higher Order Mode (HOM) - with resonant frequency around 903 MHz - excited by the beam caused sudden orbit distortions detectable at the most sensitive beam lines. 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 [1]. However, as a side effect, it increases the energy spread which is undesirable, especially for undulator beam lines.

An alternative to RF phase modulation is to use HHC which stabilize the beam without changing its energy spread and also dilutes the electrons distribution in the longitudinal direction increasing the overall beam lifetime. The installation of an Apple-II elliptically polarized undulator is scheduled for the end of 2006 and strengthens the need for an alternative to phase modulation to control the CBM instabilities as well as to increase beam lifetime.

Table 1: Basic parameters of the LNLS electron Storage Ring.

Energy	E_0	1.37	GeV
Initial current	I_0	250	mA
Main RF frequency	f_{rf}	476.066	MHz
Accelerating Voltage	V_0	500	kV

LONGITUDINAL BEAM DYNAMICS WITH 3RD HARMONIC CAVITIES

We start with a brief review of the longitudinal beam dynamics in the presence of higher harmonic cavities. The total RF voltage seen by the beam when there is a harmonic cavity in the storage ring is given by

$$V(\phi) = V_0\{\sin(\phi = \phi_s) + k \sin n\phi + n\phi_n\} \quad (1)$$

where V_0 is the peak voltage delivered by the master RF system, ϕ_s is the synchronous phase, n the ratio of the harmonic to the main frequency, which in this case is 3, k the relative harmonic voltage and ϕ_n the harmonic phase.

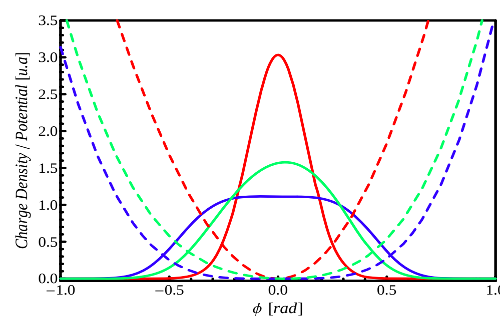

Figure 1: Longitudinal beam profile (full) and potential well (dashed) for different situations. (Blue) Main RF only and (Red) Main RF and HHC at optimum condition, (green)Main RF and HHC slightly detuned.

The motion of the particles in the modified potential well is then governed by

$$\ddot{\phi} + \frac{\omega_s^2}{V_0 \cos\phi_s} V(\phi) = 0 \quad (2)$$

and the amplitude dependent synchrotron frequency, for the maximum lengthening condition is [2]

$$\omega_s(\phi) = \omega_{s0} \frac{\pi}{2K(1/\sqrt{2})} \sqrt{\frac{n^2-1}{6}} \hat{\phi} \quad (3)$$

where $K(1/\sqrt{2}) = 1.85$ is the complete elliptic integral. The rms bunch length is given by

$$\sigma_\phi = \frac{2}{K(1/4)} \sqrt{\frac{\eta h \pi \sigma_\epsilon}{Q_{s0}}} \left(\frac{3}{n^2-1}\right)^{1/4} \quad (4)$$

where $K(1/4) = 3.62$, σ_ϵ is the rms energy spread and Q_{s0} the unperturbed synchrotron tune.

A 3rd harmonic cavity is designed so that when its field is summed with the main RF field the first and second derivatives of the potential are zero at the synchronous phase. The effect of such harmonic field is the flattening of the potential well and, as a result, the bunch lengthens as show in Figure 1. Harmonic cavities can be operated in two different modes, related to how the gap voltage in the cavities is produced. In the active mode an external RF power source delivers the necessary power to produce the gap voltage that modifies the RF potential well seen by the beam. In the passive mode, the harmonic cavities are excited by the beam itself. In this mode the main RF system supplies the power necessary to excite the harmonic fields induced by the beam. Even though it is the cheapest solution, the passive operating mode has some disadvantages. Since the main parameters of the harmonic cavities, R_s and Q_0, are fixed by its geometry, there are not enough free parameters to adjust the phase and amplitude of the excited fields. The consequence is that the optimum bunch lengthening condition is obtained only for a single value of the total beam current.

Increase in Beam Lifetime

In order to calculate the effect of the harmonic cavities on the beam lifetime, consider the expression for the Touschek lifetime

$$\tau_t \propto \frac{\sigma_x \sigma_y \sigma_z \varepsilon_{RF}}{N_b} \quad (5)$$

where σ_j is the bunch length in each direction and N_b the number of electrons in the bunch. The effect of the harmonic cavity is to increase the bunch length (σ_z) by a factor of 3 but it also reduces the RF acceptance ε_{RF}. However this variation is not very significant, of the order of 3 to 5 %, and much smaller than the net increase in σ_z.

For a passive system the amplitude of the excited fields strongly depends on the beam current. A set of simulations have been performed in order to observe how the effectiveness of the harmonic cavities changes as the stored current drops along a user shift [3]. The harmonic system is configured so that the optimum current is at 300 mA. The simulation was extended to the case where the filling pattern is not uniform and there is a gap in the bunch distribution. Table 2 shows the results of these simulations. Notice that the last column shows the resulting increase in beam lifetime based on lifetime measurements performed in the machine [4] and on the predicted increase in bunch length. Also observe that the transient effects due to the non uniform electron distribution are not as dramatic as in other machines [3] and that the 3rd harmonic slowly becomes less effective as the current drops in a range of 100 mA, until it no longer modifies the longitudinal electron distribution.

Table 2: Simulation Results for a passive 3rd harmonic cavity, considering $V_0 = 500$ kV, $R_s = 3.1$ MΩ and $Q_0 = 21000$.

I_{tot} (mA)	*Gap* (%)	Bunch Length Increase	$\Delta\tau_{tot}^{a,b}$
300	0	2.87	32%
300	10	1.98	22%
300	20	1.6	16%
300	50	1.44	13%
250	0	1.48	14%
250	20	1.40	12%
200	0	1.16	6%
200	20	1.16	6%

Suppression of Unstable Coupled Motion

The suppression of unstable CBM is given by an increase in the frequency spread caused by the harmonic cavity. It is possible to estimate the increase in stability by taking into account equations (3) and (4) and also supposing that the damping time can be written as

$$\frac{\tau_{3rd}}{\tau_{nat}} = \frac{\Delta\omega_{nat}/2\pi + 1/\tau_{rad}}{\Delta\omega_{3rd}/2\pi + 1/\tau_{rad}} \quad (6)$$

where $\tau_{rad} = 3.7$ ms is the radiation damping time and $\Delta\omega_{nat} = 2\pi 170$ Hz is the natural frequency spread. Evaluating this expression with actual parameters we find that $\tau_{3rd}/\tau_{nat} \approx 1/16$, indicating that the damping time in case there is a 3rd harmonic cavity installed in the ring is reduced by a factor of 16. The harmonic system is thus able to damp most of the potential longitudinal CBM instabilities caused by harmful HOM present in the main RF cavities [1].

Another way to observe the effects the stabilization due to a harmonic cavity is to plot a stability diagram [2]. In this plot the area which encloses the origin indicates a stable operation region and the outside area correspond to unstable solutions. The stability diagram is defined as

$$U + iV = -i\Delta\omega_{coh} = \frac{1}{I(\Omega)} \quad (7)$$

where

$$I(\Omega) \equiv \frac{\pi}{2} \int_0^\infty \frac{r^2 dr}{\Omega - \omega(r)} \frac{\partial \Psi_0(r)}{\partial r} \quad (8)$$

where $\Psi_0(r)$ is the electron distribution in phase space.

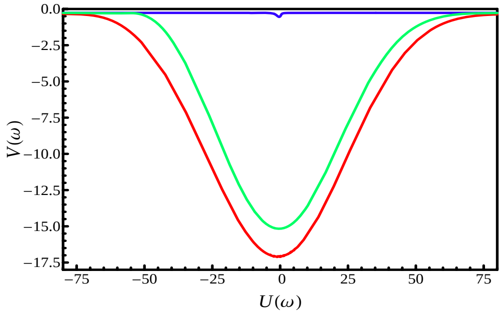

Figure 2: Longitudinal stability : (blue) main RF only, (red) 3rd harmonic cavity and (green) 3rd harmonic cavity slightly detuned corresponding to the situation of 250 mA and gap = 0% in Table 2.

The stability diagram is in Figure [2] for the case with and without the 3rd harmonic cavity, note that the stable area is greatly increased when the harmonic cavity is present.

3RD HARMONIC CAVITY

The main goals that guide the design and construction of the harmonic cavities are, on the one hand, the unflagging need for high shunt impedance and, on the other, simplicity, on the engineering standpoint.Although the cavities are planned to operate in the passive mode the possibility of active operation is taken into account in the design. For the nominal operation conditions of the LNLS storage ring the gap voltage needed for optimum effective operation of the cavities is 145 kV. The nominal gap voltage in the main RF system is 500 kV. Table 3 shows the total shunt impedance ($R_{sh} = V^2/(2R)$) needed to produce the optimum gap voltage for different values of stored current.

Since simplicity is taken as the main goal, the design of the cavity is based on the simple cylindrical pillbox geometry. The geometry was optimized in order to obtain the maximum shunt impedance. The simulated value of the shunt impedance is 1.6 MΩ and the Q-factor is 23000. In order to extend the range of optimum operation of the harmonic system even to lower beam currents 4 cavities are planned to be installed. The experience with the main RF system pointed to the importance of avoiding the HOM of the cavities. That can be accomplished either by detuning the cavities, using the movable tuner and changing the water temperature, or by reducing the Q-factor of the most harmful HOMs by the addition of a damping antenna. A prototype of the cavity is under construction at the LNLS workshops and will allow a more detailed analysis on how to damp or tune out the undesirable modes. The design includes four ports that will be used for tuning, HOM damping, and for vacuum and rf monitoring.

Table 3: Total shunt impedance needed for optimum operation at the passive mode for different values of stored beam current.

I_{tot} (mA)	R_{shunt} (MΩ)
150	6.1
200	4.6
250	3.7
300	3.1

CONCLUSION

A prototype third harmonic Landau cavity is under construction at the LNLS workshops. Four of these cavities are planned to be installed in the storage ring in order to control CBM instabilities generated by the main RF system cavities and also to increase beam lifetime.

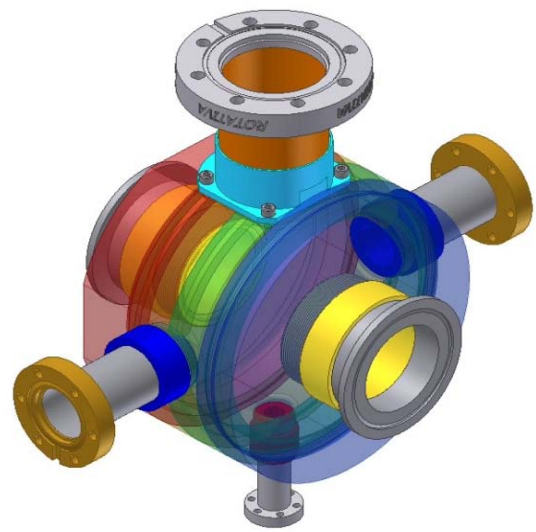

Figure 3: 3-D CAD drawing of the prototype third harmonic cavity.

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