BENCH CHARACTERIZATION OF A PROTOTYPE OF A 3RD HARMONIC CAVITY FOR THE LNLS ELECTRON STORAGE RING

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Abstract

The UVX electron storage ring at the Brazilian Synchrotron Light Laboratory suffers from longitudinal instabilities driven by a HOM of one of the RF cavities. The operational difficulties related to these unstable modes were successfully overcome by determining the proper cavity temperature set point in combination with phase modulation of the RF fields at the second harmonic of the synchrotron frequency. However, a serious drawback of the method is to increase the energy spread of the electron beam, which is detrimental to the undulator emission spectrum. The use of higher harmonic cavities is a more appropriate technique since it provides damping of the longitudinal modes without increasing the energy spread. A full scale prototype of a 3rd harmonic cavity was manufactured at the LNLS workshops and had its main rf properties measured. Special care was taken to measure the shunt impedance of the fundamental resonant mode since it determines how many cavities will be necessary for the adequate operation of the system, which is designed to operate in passive mode. In this work we present the results of the bench characterization of the cavity.

INTRODUCTION

The LNLS Synchrotron Light Source is based on a 1.37 GeV electron storage ring. The machine operates with 14 beamlines open to external users 24 hours a day, 5 days a week, delivering 4100 hours at 97% reliability in 2007. The injection system comprises a triode-type thermionic gun, a 120 MeV linac and a 500 MeV booster synchrotron. The accumulation process takes place at 500 MeV and the beam is ramped up to 1.37 GeV. At the standard multibunch operation mode the initial beam current is 250 mA in routine user shifts.

Instability problems related to a longitudinal Higher Order Mode (HOM) in one of the RF cavities - with resonant frequency around 903 MHz - led to the adoption of phase modulation of the RF fields at twice the synchrotron frequency. The HOM, once excited by the electron beam, caused sudden orbit distortions detectable at the most sensitive beam lines. The phase modulation has a noticeable impact on CBM amplitudes and helps alleviate the orbit fluctuation [1]. However, as a side effect, it also increases the energy spread of the electron beam, which is especially undesirable for undulator's beam lines.

An Apple-II elliptically polarized undulator, designed and built at the LNLS was installed in 2007 [2] and the

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

beam line is in its final stages of project and assembling. That strengthens the need for an alternative to phase modulation both to control the CBM instabilities and to increase beam lifetime.

An alternative to RF phase modulation is to use higher harmonic cavities 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 3RD HARMONIC CAVITY

A prototype of the landau cavity was designed and fabricated at the LNLS workshops. The main design guideline was construction simplicity, so that the design of the cavity is based on a cylindrical pillbox geometry. The geometry was optimized in order to obtain the maximum shunt impedance. The simulated value for the shunt impedance of the fundamental 3rd harmonic mode is 1.6 MΩ and the Q-factor is 21000.

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. The cavity has openings for a tuning plunger, for a HOM damping coupler and vacuum, for a future power coupler and an antenna for the tune control loop.

The detailed design of the cavity prototype was driven by costs constraints, trying to make maximum use of supplies available in the Brazilian market. The cavity was assembled from pieces machined from four 50 mm thick OFHC copper slabs. Three of these pieces were brazed together and the fourth piece was designed as a screwable cap such that some tuning tests could be performed. The prototype has embedded water cooling channels although no temperature control was used during the measurements reported here.

The cavity will operate in passive mode although the design foresees the possibility of active operation. One of the ports can be used as an RF power input port. In the passive

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Table 2: 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

mode the amplitude of the excited fields is determined by the beam current, so that the effectiveness of the passive cavities changes as the stored beam current drops along the user shift. The system has to be dimensioned aiming at the maximum useful operation in the current ranges during typical user runs.

For the nominal operation conditions of the LNLS storage ring, the gap voltage needed for optimum effective operation of the cavities is 145 kV [3]. The nominal gap voltage in the main RF system in multibunch users shifts is 500 kV. Table 2 shows the total shunt impedance ($R_{sh} = V^2/(2R)$) needed to produce the optimum gap voltage in the 3rd harmonic system for different values of stored current.

For an efficient passive operation at 200 mA the total shunt impedance of the installed cavities should amount to 4.6 MΩ. That shunt impedance would allow the cavities to be efficient for currents ranging from 250 mA down to 170 mA [3], which is the current range during typical users shift.

MEASUREMENT SETUP

In order to determine how many cavities should be installed in the storage ring it is fundamental to know the effective shunt impedance of the real cavities. For that purpose a measurement workbench was set up also aimed at simplicity. The measurement setup was assembled in the RF lab.

The measurement of the main electrical characteristics of a resonant cavity demands few instruments. A Network Analyzer, a small conductive sphere, a piece of thread made of dielectric material and a ruler would suffice to measure the shunt impedance, if the desired accuracy was not very high. To identify the higher-order modes we need only a dielectric rod and a piece of conductive wire, besides the Network Analyzer.

The setup is very simple, known since the classic paper of Meier and Slater [4]. We used a computer to drive a small stepper motor and to automatize the measurements of the Network Analyzer. The step motor pulls a dielectric thread that can be moved along with the cavity axis. Attached on it is a small metallic sphere, which will disturb the electromagnetic field configuration of the resonant modes excited in the cavity. Since there is no temperature control either on the cavity itself or in the RF lab, the system was optimized to perform the measurement as fast as possible.

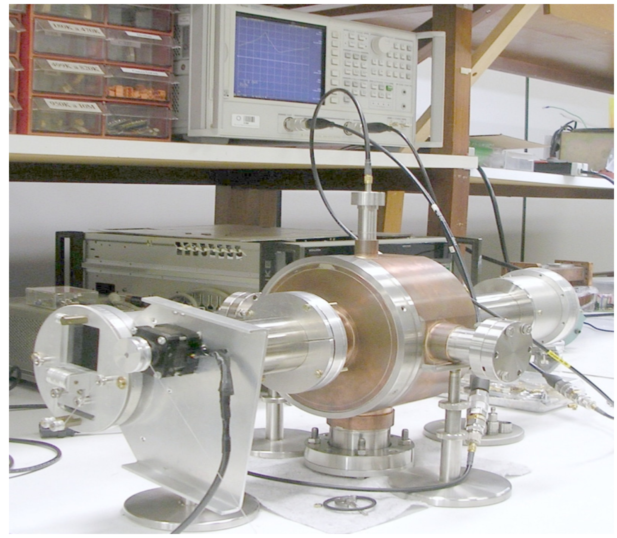

Figure 1: The prototype harmonic cavity and the measurement setup.

Measurement Considerations

The measurement is subject to some sources of errors. As an example, we can name the variations on the resonant frequencies with the room temperature and the low coupling of the antennas used, which can result in considerable background noise in the measurements. We are willing to accept an error of 10% in the measurement of the R/Q parameter, which is basically dependent on the internal geometry of the cavity. We are basically interested in the measurement of the fundamental resonant mode since it will point us to the number of cavities needed to have the passive harmonic system working.

When a spherical bead is used the effective shunt impedance of a resonant mode is given by [4]

$$\frac{R_{eff}}{Q} = \frac{1}{4\pi f_0 \xi}\left[\int \sqrt{\frac{\Delta f}{f_0}(z)}\cos\left(\frac{2\pi f_0 z}{c}\right)\mathrm{d}z\right]^2 \quad (1)$$

where $\xi = \epsilon_0 \pi r^3$ is the form factor for a metallic bead of radius r, f_0 is the frequency of the undisturbed mode and Δf is the frequency shift produced by the bead as it crosses along the cavity axis.

In order to minimize the error of the measurements, we chose to make it fast, so that temperature transients in the lab did not affect the results. For each different setup configuration a series of measurements were performed and the whole set of measurements was then averaged. By optimizing parameters such as the number of acquisitions and average factor, we were able to perform the measurement of the shunt impedance within 10 minutes.

The measurements are very repetitive, since none of them deviated more than 5% from the average result obtained. We tested polyamide fishing threads of different diameter trying to minimize the sag produced by the bead and the lengthening produced by the counterweight used to

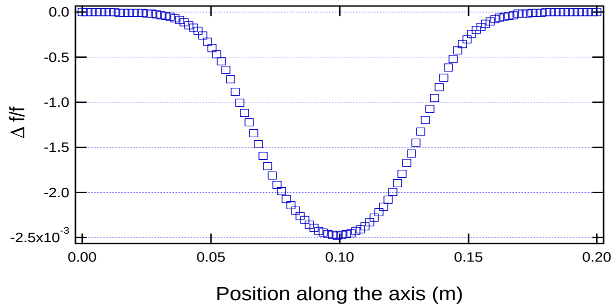

Figure 2: Typical variation of $\Delta f/f$ obtained for the fundamental mode as the bead crosses the cavity.

keep the thread stretched. The measurements are not sensitive to the diameter of the thread used and even to the bead diameter, once it is large enough to produce a frequency shift which is large compared to the background noise of the frequency measurement. Most of the measurements were performed with a 8.1 mm diameter metallic spherical bead. We tested metallic beads ranging from 3 to 12 mm diameter. The results are indistinguishable for the larger beads but for the smaller ones the precision of the measurement is very low. The measurements are also not very sensitive to the size of the step.

Measurements off the central axis were also explored. The bead was moved along trajectories set parallel to the cavity axis but at different offsets. The results are not greatly affected by the offset, at least for distances of the order of the sag produced by the bead. That also shows that the electric field is fairly constant at the spheres volume for the fundamental resonant mode. The values obtained were not very different from those obtained on axis.

Results

Unfortunately, once we designed the prototype with an attachable screw cap, we introduced a large source of measurement error, particularly in the determination of the quality factor of the resonant modes. That forced us to use the quality factor obtained from numerical simulations of the cavity in order to obtain the shunt impedance of the fundamental mode. The main effect of the bad RF sealing provided by the screw cap is to lower the Q-factor of the modes due to the exposure of the RF fields to the low conductivity stainless steel screw thread.

However, notwithstanding the problems related to the measurement of the Q-factor, it was possible to obtain very good agreement between the calculated R/Q factor and the measured one. The results are very repetitive, for different experimental conditions ranging from bead sizes to small misalignments purposely introduced in the trajectory of the bead along the cavity axis.

Table 3: Longitudinal and dipolar resonant modes of the 3rd Harmonic Cavity

F_{meas} **(GHz)**	F_{calc} **(GHz)**	**ID**	R_{sh} **(MΩ)**
1.442	1.432	L0	1.6
2.123	2.129	T1	-
2.180	2.165	T2	-
2.340	2.324	L1	0.3

Table 4: Measured parameters of the fundamental resonant mode of the Landau Cavity. The simulated values refer to 2D simulations of the cavity.

	Measured	St. Dev.	Simulated
Frequency	1.442	-	1.428
R/Q (Ω)	187.7	4.76	196.7
R/Q_{eff} (Ω)	72.6	1.4	76.2
R (MΩ)	3.9	0.1	4.13
R_{eff} (MΩ)	1.52	0.03	1.6

A primary source of measurement errors comes from moving the bead along the cavity. To know the absolute position of the bead is not relevant but the same is not true of how precisely each step can be determined. It is important to be careful in order to ensure an accurate measurement of the length of the steps taken by the bead along its trajectory. For the fundamental mode of the prototype cavity, a 5% systematic error in the step length would lead to an error of 10% in R/Q.

Table 4 shows the results of the measurements performed for the fundamental mode of the Landau cavity. R/Q was measured and the shunt impedance was obtained taking into consideration the simulated value of the Q-factor.

CONCLUSION

A set of measurements were performed on a prototype of the landau cavity planned to be installed in the LNLS storage ring. The results show an effective shunt impedance of 1.5 MΩ for the fundamental mode. In order to obtain the total shunt impedance needed to have the passive system working at most of the current range during a typical users run it will necessary to install 3 cavities in the storage ring. The measurements showed fairly good agreement with the simulated values, although performed on a very simple setup.

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