DESIGN AND IMPEDANCE OPTIMIZATION OF THE LNLS-UVX LONGITUDINAL KICKER CAVITY

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Abstract

Performance evolution of parameters achieved during the electromagnetic design of the longitudinal kicker cavity for the LNLS UVX storage ring is presented. The effort on the electromagnetic optimization process of the heavily loaded cavity has been made to reach the required electrodynamic parameters of the kicker. The results for three different geometries are compared and a good compromise between the longitudinal shunt impedance and the effect of the longitudinal Higher Order Modes (HOM's) on beam stability has been found.

INTRODUCTION

The UVX storage ring, the actual light source from LNLS, the Brazilian Synchrotron Light Laboratory, have always been suffering from longitudinal Coupled Bunch Mode Instabilities (CBMI's) since its RF System commissioning. The adoption of the RF phase modulation keeps the instabilities under control [1] for most of the experiments. The bunch lengthening caused by the RF phase modulation does not affect the users. The initial purpose of implementing a longitudinal feedback system was using the present light source as a bench test for Sirius, the next Brazilian 3rd generation synchrotron light source. More recently some drawbacks of the RF phase modulation appeared:

- During the commissioning of the fast orbit feedback (FOFB) [2] the negative effect of the huge synchrotron oscillations was clearly observed; aliasing of the synchrotron sidebands produced low frequency noise in the BPM readings. A fine tuning of the FOFB clock signals had to be done in order to reduce the noise produced by the aliasing. The tuning system needs to be applied in every event that provokes a change in the amplitude or frequency of the synchrotron oscillations;
- The studies for implementing a low-emittance optics in the LNLS UVX storage ring also highlighted the need of bunch-by-bunch (BBB) feedback systems. Large vertical instabilities showed up during the tests limiting the beam size reduction. The tests with beam indicated that huge longitudinal instabilities can prevent the transverse feedback systems of working properly. This may be the main reason for implementing a longitudinal BBB feedback system.

This paper presents the evolution of the performance parameters achieved during the electromagnetic design of a longitudinal kicker for the UVX storage ring. The presented design is based on the worldwide reproduced waveguide overloaded cavity kicker developed originally at DAΦNE in 1995 [3] and improved at Pohang Light source (PLS) [4]. Three different geometries are compared along this document aiming to propose a good compromise between the longitudinal shunt impedance and HOM's content.

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BASIC LNLS UVX RING PARAMETERS

The UVX ring is not equipped with a full-energy booster. Every 12 hours the ring is ramped down, refilled to 250 mA, and ramped back up. The energy ramp goes from 490 to 1370 MeV in about 40 s. The main LNLS storage ring parameters are presented in Table 1.

Table 1: Main UVX Parameters at High Energy

Parameter	Value	Unit
Nominal Energy, E_0	1.37	GeV
Circulating current, I_{av}	250	mA
Circumference, C	93.2	m
RF frequency, F_{RF}	476.066	MHz
Harmonic number, M	148	--
Bunch length, σ_S	11	mm
Horizontal tune, ν_x	5.27	--
Vertical tune, ν_s	4.17	--
Synchrotron frequency, ω_s	25*2π	krad/s
Momentum compaction, α	0.0083	--
Energy spread, ΔE/E	0.281	%
Horizontal damping time	7.8	ms
Vertical damping time	7.5	ms
Synchrotron damping time	3.7	ms

ELECTROMAGNETIC PROJECT

The LNLS longitudinal BBB feedback system is equipped to modulate the correction signal at $2.5{*}F_{RF}$. Based on this, as well as on CBMI's theory, the nearest possible center frequency for the longitudinal kicker can be 2.25 and 2.75 multiples of RF frequency, i.e., with the fundamental mode centered at these frequencies, all possible CBMI's can be covered within a ½ F_{RF} (238 MHz) bandwidth (BW). The shunt impedance increases with F_c and our decision is to take $F_c = 2.75{*}F_{RF}$ (1.31 GHz). The initial goal was to achieve the higher shunt impedance as possible with several geometry parameter sweeps. The HOM's analysis was made together with CBMI's growth rate (GR) calculations to achieve a conservative GR, under 10% of UVX storage

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ring damping rate (DR). The main design goals of the electromagnetic project are summarized in Table 2.

Table 2: Required Parameters for the LNLS Kicker Cavity

Parameter	Value
Center Frequency (11/4 F_{RF}), F_c	1.31GHz
Min. Bandwidth (1/2 F_{RF}), BW	238MHz
Max. desired CBMI GR	10% of DR

Geometry Sketch

The kicker parameterization pattern presented in Fig. 1 follows the same one employed by PLS for electromagnetic modeling [3]. The entire design process of the longitudinal kicker for UVX can be divided into stages that can be represented by three different geometries, whose parameters are shown in Table 3. As will be presented in the next sections, Geometry 3, depicted in Fig. 1, was chosen as the final geometry since it satisfies the requirements presented in Table 2.

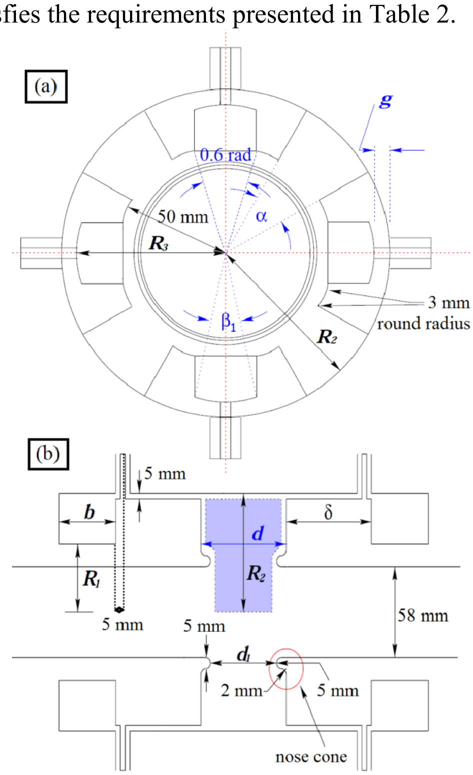

Figure 1: Geometry sketch of the longitudinal kicker [4]. a) Axial-cut view. b) Side-cut view.

Such cavity can be represented as a pillbox cavity with 4 ridged waveguides (see Fig. 1a) on each side. Each ridge waveguide has one attached feedthrough. One side of the kicker receives the correction signal from the amplifiers, which is dissipated on external dummy loads attached to each waveguide output from the opposite side of the cavity. The BW of the fundamental TM_{010} mode increases significantly with the number of waveguides in the cavity. The downstream Four Waveguides Assembly is is rotated around the longitudinal axis by 45º relative to the four upstream ones.

Table 3: Geometric Parameters for the Three Kicker Models Considered for the UVX Storage Ring

Geometric Parameters (mm or rad)			
Parameter	Geom. 1	Geom. 2	Geom. 3
R2	84	82	84.7
R3	79	77	79.7
α	0.42	0.42	0.2
β	0.25	0.25	0.39
d	74	67	52.8
δ	50.2	55	42
b	52.3	52.3	25

Design Process

The procedure for designing the overloaded cavity which would attend UVX requirements was based on initially rescaling PLS design to our vacuum chamber diameter and desired center frequency. The entire design process consists on correctly setting the shunt impedance curve and analysing the CBMI's brought by the cavity. Since solving one can affect another, the process may be done iteratively.

Multiple parameter sweeps were performed to set the longitudinal shunt impedance curve, with maximum amplitude and with minimum required BW. The CST Microwave Studio code [5] has been used for the electromagnetic simulations. The longitudinal shunt impedance is defined by

$$R_{sh} = \frac{\left|V_{gap}\right|^2}{2P} . \qquad (1)$$

where P is the kicker total input RMS power and V_{gap} is the gap voltage defined by

$$V_{gap} = \int_{-L/2}^{L/2} E_z e^{j\left[\omega\frac{z}{c} - \phi_E(z)\right]} dz . \qquad (2)$$

where L is the kicker length and $E_z(z)$ and ϕ_E (z) are the longitudinal electric field magnitude and phase, respectively, along the beam axis. Fig. 2 illustrates the electric field pattern of the TM_{010} mode.

After dimensioning the geometric parameters to obtain a satisfactory R_{sh} curve, the HOM's content of the cavity must be carefully analyzed. With the obtained coupling impedance spectrum, the CBMI's GR can be calculated in order to check if it is below the desired 10% DR factor. This work will show results only for the longitudinal case.

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No concerns have appeared for any of the 3 geometries that for the results obtained by the transverse analysis.

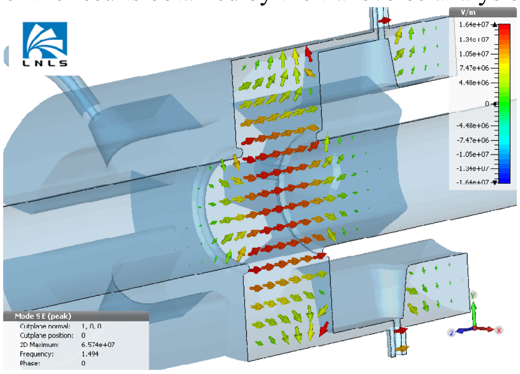

Figure 2: The electric field pattern of TM_{01} mode calculated with CST.

The CBMI's GR has been calculated according to the Wang formalism [6], resulting in the Eq. 3 below for the longitudinal case, at zero chromaticity:

$$\mathrm{Im}(\Delta\omega) = \frac{1}{\tau_\mu} = \frac{I_B M \omega_0^2 \alpha}{4\pi(E_0/e)\omega_s} \sum_{p=-\infty}^{p=+\infty} \Bigg[(pM+\mu)^2 \cdots \qquad (3)$$

$$\cdots e^{-(pM+\mu_s)^2 \left(\sigma_s/R\right)^2} \frac{\mathrm{Re}\, Z_{\|}(pM\omega_0 + \mu\omega_0 + \omega_s)}{(pM+\mu+\upsilon_s)} \Bigg]$$

for the dipole mode a = 1 and for Gaussian bunches with uniform filling. The related parameters follow Table 1 notation. Additionally, $I_B = I_{av}/M$ is the average bunch current, $\omega_0 = 2\pi F_{RF}/M$ is the revolution frequency and $R = C/2\pi$ is the average ring radius.

If the designed cavity did not attend an acceptable GR value, solutions that implied changes in geometry parameters were tried. Since modifications in geometry also change the shunt impedance curve, all design loop of this subsection, described up to this point, must be redone, until all requirements are reached.

Geometries Optimization can be illustrated by Fig. 3, which shows the longitudinal beam impedance for the three geometries. The process has started with Geometry 1 being the one that came up from rescaling and adapting PLS design. However, from Eq. 3, its CBMI's GR was found to be 20% of synchrotron DR. The own fundamental mode was exciting the fastest CBM. From Geometry 1 $F_c = 1.31$ GHz, we found that if we apply a 40 MHz center frequency shift on the fundamental mode, the CBMI's requirements would be reached. This shift was then applied onto Geometry 2 with the changes listed in Table 3, leading to wider bandwidth and lower coupling impedance, generating higher growth rates though (~25% of DR). In this case, the longitudinal mode L3 at frequency 3.32 GHz is trapped and excites the fastest CBM. Therefore we started working with the possibility of damping L3, which later led to Geometry 3. The calculated fastest CBM excited by this final geometry has its GR in the order of 9.7% of the synchrotron DR.

Comparing blue and orange lines from Fig. 3, we can see how strongly the L3 mode was damped. For doing this, we considered three options: a) introducing ferrite; b) inserting loop antennas; c) or performing a fine optimization of the ridged waveguide, as presented at next subsection.

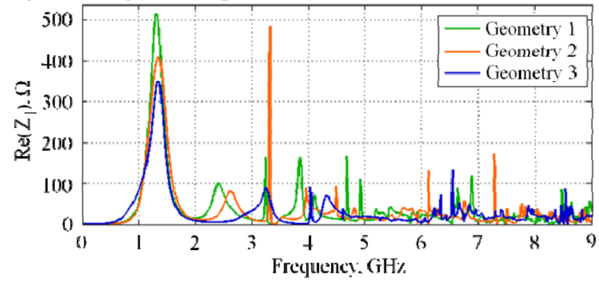

Figure 3: The longitudinal coupling impedance for the three different geometries.

Ridged Waveguide Optimization

The ridged waveguide model (vacuum profile) used on the optimization process can be seen in Fig. 4.

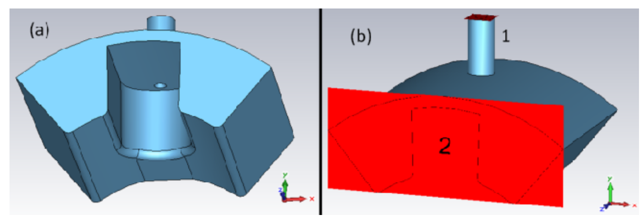

Figure 4: Vacuum profile of the ridged waveguide. a) Perspective view. b) Port 1 and port 2 assignment.

The simulated S-parameters are compared for the three geometries, which are discussed in this document. The transmission coefficient (S2,1) is shown in Fig. 5. As can be seen by the markers 2 and 3, the cutoff frequency of the ridged waveguide for Geometry 3 has been reduced by 216 MHz to allow the trapped longitudinal mode L3 be coupled through the coaxial feedthrough. One can also see why this mode grew stronger from the first to the second kicker design, when markers 1 and 2 are compared. The cutoff frequency has increased by 22 MHz.

After waveguide optimization, its geometric parameters were kept fixed and the remaining parameters of the global kicker structure were readjusted in order to have a 700 Ω shunt impedance, 1.35 GHz center frequency and a 300 MHz BW. The BW was set larger than requirements in order to compensate the +40 MHz center frequency shift.

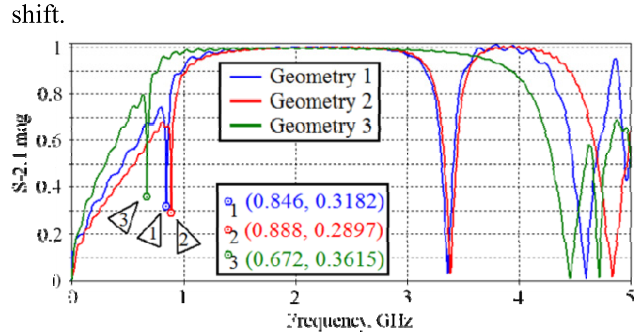

Figure 5: Ridged waveguide – S2,1 for all 3 geometries.

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EM CHARACTERIZATION

Geometry 3 was later sent to engineering design and machined at our local Machine Shop. Fig. 6 shows the resulting structure.

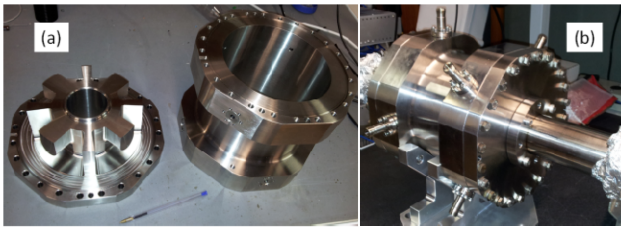

Figure 6: Machined UVX kicker cavity. a) Disassembled: one side of the cavity (left) with 4 waveguides and the cavity chamber (right). b) Assembled structure.

After assembling the waveguides with the chamber and attaching all feedthroughs, the microwave measurement setup was set, just as shown in Fig. 7. The characterization process was focused on comparing the measured S-parameters and the shunt impedance curve with the simulation results [7].

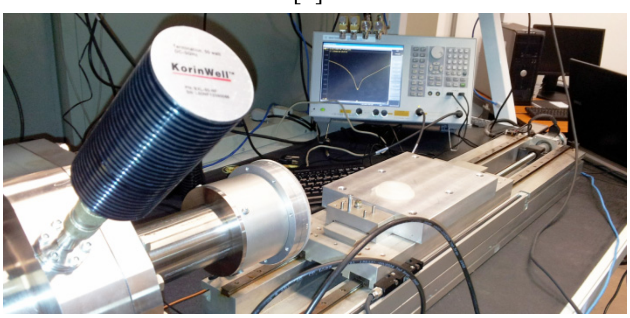

Figure 7: Microwave measurement setup: loaded kicker, network analyzer and sliding platform.

S1,1 parameters were not only calculated by simulations but also measured by simultaneous excitation of four feedthroughs on the same side. During the simulations it can be easily done by taking advantage of quarter symmetry. For the measurements, Port 1 of the network analyzer was connected to a 4-way splitter that feeds the downstream ports. The upstream ports were matched with 50 Ω loads. Fig. 8 highlights the comparison between simulation and measurements data. We can observe 8.2 MHz difference between center frequencies and 30 MHz difference on BW's.

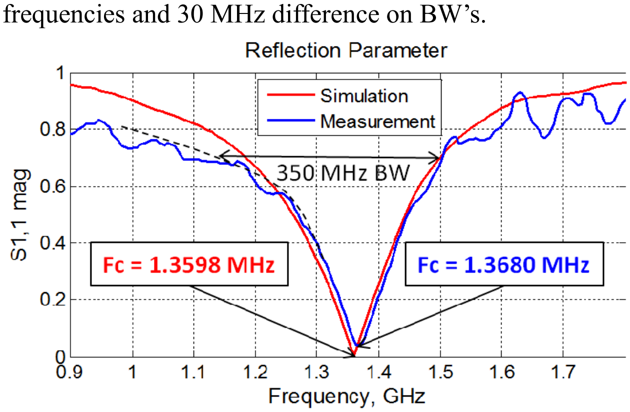

Figure 8: Measured (blue) and simulated (red) S1,1 parameters.

One important point to that needs to be highlighted here is the difference between the parameters obtained from R_{sh} and S1,1 curves on simulation: later gives a BW = 320 MHz and F_c = 1.36 GHz, against BW = 300 MHz and F_c = 1.35 GHz from the former (as already mentioned on previous section). Therefore, in order to calculate the shunt impedance using the measured data, a 330 MHz BW was considered.

The bead-pull method was applied for shunt impedance measurement. It was set-up with a sliding platform which moves with the rotation of a threaded axis attached to a step motor (Fig. 7). The platform movement was measured by an encoder attached to it. A nylon string, which was holding a 6 mm radius metallic bead, was centered by a pulley system and had one end tied to the platform and other to a load. For each platform movement step, the center frequency was tracked due to S1,1. The measured R_{sh} is 700.7 Ω, for a 330 MHz BW.

CONCLUSIONS

The LNLS longitudinal kicker geometry has been modified during the optimization process. To be more specific, the ridged waveguide geometry has been optimized from reflection and transmission coefficients point of view in order to improve the kicker coupling impedance by damping L3 mode. The overloaded cavity is already installed in the storage ring and the BBB longitudinal feedback system is in commissioning phase.

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