ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB332

DESIGN OF 4th HARMONIC RF CAVITIES FOR ESRF-EBS*†

A. D'Elia, V. Serrière, J. Jacob and X. Zhu, ESRF, Grenoble, France

Abstract

An active 4th harmonic RF system for bunch lengthening is under study at the ESRF to improve the performance of the new EBS storage ring (ESRF-EBS SR), mainly for few bunch operation with high currents per bunch, by reducing Touschek and intrabeam scattering, thereby increasing the lifetime and limiting the emittance growth. It will also reduce impedance heating of the vacuum chambers. The 4th harmonic 1.41 GHz normal conducting cavity design takes inspiration from the KEK idea of using a TM020 mode exhibiting a reduced R/Q but a higher unloaded Q with respect to TM010 [1]. We propose to use multicell cavities for their compactness, the reduced number of required ancillaries and the ease of control for a reduced number of cavities. The drawback is the complexity of the model and the necessity to damp the lower order TM010 mode (LOM) as well as the higher order modes (HOM). The RF design of a 4th harmonic multicell damped cavity will be presented.

INTRODUCTION

The new ESRF-EBS SR is back operational in user mode (USM) since August 2020 and provide for one of the most brighter and coherent X-rays beam worldwide. This is possible thanks to the extremely small emittance of the circulating electron beam. The main drawback of these very small beam size is a larger intrabeam and Touschek scattering with a consequent reduction of the lifetime implying more frequent injection with a larger loss rate and radiation load. Higher is the current per bunch more dramatic is the lifetime reduction. Indeed, the lifetime is foreseen to drop to 3.5 hours for the 16 bunches and to 2.5 hours for the 4 bunches. A harmonic system is therefore mandatory for these operation modes. A second, high, priority to install a harmonic system is related to the mitigation of the heat-load and the stress on critical chambers, like ceramic chambers or In-Vacuum IDs. Presently we need to limit the operation to a maximum of 30 mA in 16 bunches (usually at 92 mA) and 16 mA in 4 bunches (usually at 40 mA) until the installation of new ceramic chambers in one year from now. Besides these high priorities, there are also other aspects that will benefit from a harmonic system: improvement in the overall stability, reduction of the emittance and energy blow-up.

A 4th harmonic system at 1.41 GHz would provide for a bunch lengthening between 2.5 and 3, with a required optimum harmonic voltage of 1.49 MV[1] (1.98 MV for a 3rd harmonic system). For this frequency range there is a better availability of RF power sources. The use of a TM020, if on one hand add the complexity of the LOM suppression, on the other hand allows to mitigate the tight tolerances and the mechanical difficulties arising from the reduced size of the structure. The possibility of a multicell structure, despite of its complexity in the design, allows to reduce the number of auxilaries and to facilitate their distribution all over the cavity, simplfying the mechanical integration. Moreover the structure will be more compact longitudinally which will ease to fit it inside the available space of ~1.8 m in cell 25.

In terms of beam physics performances, the TM020 mode is less sensitive to the transient beam loading than TM010, producing an improvement of the beam parameters also for non-symmetrical fillings. In non-symmetrical fillings (for ex. 7/8+1, the ESRF most used filling pattern), the bunch lenghtening from the harmonic system suffers from the phase transients that are proportional to the R/Q. A TM020 intrinsically exhibits a reduced R/Q (almost half of TM010) but a higher unloaded Q (about 50% higher than TM010) and therefore would be beneficial also for these filling patterns at the expenses of ~30% of additional power.

In the following the design of a TM020 multicell cavity and its status will be detailed.

THE ELECTROMAGNETIC DESIGN

The basic idea behind this structure is to couple the TM020 and the TM010 with the same mechanism. The TM010 (the LOM) will be damped at the extreme of the structure at the node of the TM020 electric or magnetic field. HOM dampers will be added to dilute the HOM having the same symmetry of the TM020 and to enhance the overall damping to meet the Longitudinal Coupled Bunch Instability (LCBI) criterion.

The X-ray trace imposes a horizontal minimum radius of the beam pipe of 45 mm. The minimum space needed to insert an adequate cooling system fixed the number of slots (four), their position and wall thickness. The standard cell with its main paramaters is shown in Fig. 1. These

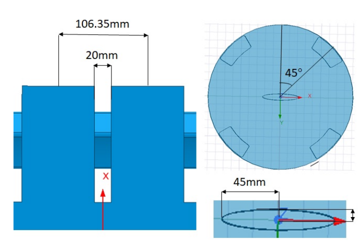


Figure 1: Standard cell with its main parameters.

preliminary studies have shown that the R/Q is negligibly impacted by the elliptical shape providing for a sufficient

* This project has received funding from the European Union's Horizon2020 research and innovation program under grant #871072.

† In accordance with resolution of government of Russian federation #287 on approval of the Federal research and engineering program for development of synchrotron and neutron studies and research infrastructure for 2019-2027.

[1] Main RF voltage of 6.5 MV, the harmonic voltage reduces to 1.35 MV (1.79 MV for a 3rd harmonic) with the present, nominal voltage of 6 MV.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB332

reduction of the vertical dimension. The presence of a nose cone does not remarkably improve the shunt impedance and is not adopted in the design.

Optimization of the TM020-π Mode

We use a double chain of coupled resonators to model the whole system and to drive the electromagnetic design [2]. Indeed, the TM020 band interacts with the closest neighbour TE band and this interaction needs to be included in the model (see Fig. 2).

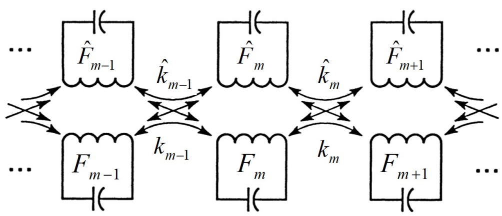


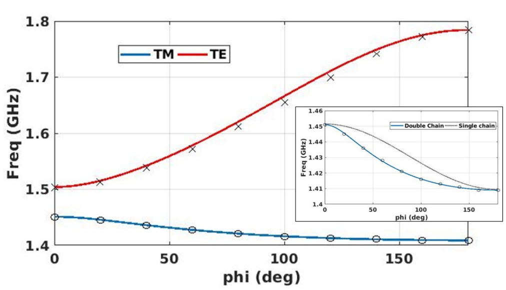
Figure 2: Equivalent circuit representation: m is the cell index, F_m is the single cell frequency, k_m the coupling constant between two adjacent cells. The quantities with the symbol "^" refer to the TE mode.

The relation dispersion for an infinite chain of resonators can be promptly found by treating all the parameters as indipendent on m, Eq. (1):

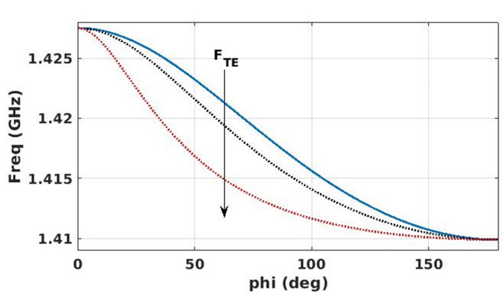
$$\left(\frac{1+\hat{k}\cos\phi}{\hat{F}^2}-\frac{1}{\hat{f}^2}\right)\left(\frac{1-k\cos\phi}{F^2}-\frac{1}{f^2}\right)-\frac{k\hat{k}}{F^2\hat{F}^2}\sin^2\phi=0, \tag{1}$$

f and $\hat{f}$ are the modal frequencies of the TM and TE mode respectively, with a phase advance ϕ from cell to cell.

An example of the model prediction can be seen in Fig. 3(a), inset a comparison with a single chain model.



(a) Model prediction vs HFSS simulation data



(b) Effect of TE-TM interaction

Figure 3: Brillouin diagrams.

The interaction between the bands gives an upper limit in the coupling slot aperture. Indeed, when the coupling slot opens, the TE and TM bands approach and their interaction becomes stronger. Figure 3(b) shows a numerical experiment where the TE mode is lowered to approach the TM band: the spacing of the modes close to π is largely reduced. A 5-cell structure with a slot aperture above 28^o exhibits a spacing <1 MHz of the π mode to its closest neighbour.

The condition for the end cell termination of the TM020-π mode is found to be the same as for a single chain. Figure 4 shows the absolute value of the electric field on axis of a 5-Cell after compensation.

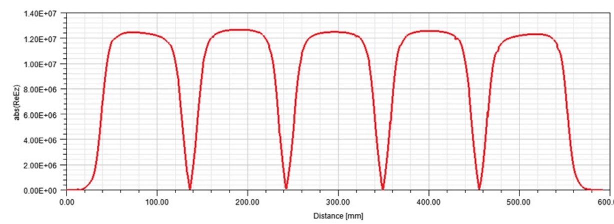


Figure 4: Profile of the absolute value of the electric field on axis.

Table 1 shows the main parameters for different slot apertures. A single multicell structure would require an unrealistic amount of power while twice a 4/5-cell brings the power to reasonable values (evaluated for $V_{4,opt}$=1.49 MV). To reduce the heat-load on the ceramic windows, we will use two couplers per structure. The value of k_{TM010} gives

Table 1: Power for Different Configurations

	2X5-Cell	**2X4-Cell**		
Slot Aperture	27.5^o	27.5^o	25^o	23.5^o
(R/Q)/cell (Ω)	43.8	43.5	44.54	44.85
Q0	24944	24642	27191	27970
k_{TM020} (%)	2.39	2.38	1.64	1.29
k_{TM010} (%)	2.07	2.18	1.56	1.23
Spacing (MHz)	1.2	1.8	2.1	2.1
P/struc. (kW)	51	65	58	55.3

a lower limit for the slot aperture: if too low, the coupling will be too weak to ensure the damping of the LOM from the end cells. Below 23^o, k_{TM010}<1%.

LOM and HOM Damping

The suppression of the LOM is possible using four coaxial antennas on each end cell coupling the TM010 electric field.

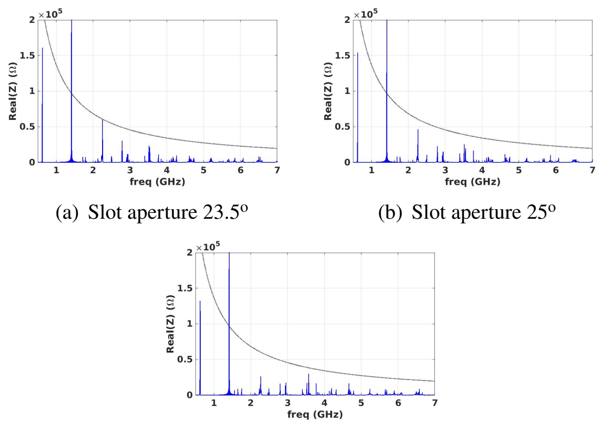
The penetration of the LOM antennas is limited by the frequency shift (lowering) induced in the end cells that, beyond a certain value, lose the coupling with the rest of the structure. From the simulations we also see that the antennas must be placed with a precision of ±0.1 mm.

The LOM antennas couple to a certain extent also the HOMs, save the ones with the same symmetry of the TM020. This implies that HOM couplers are necessary to damp all

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB332

the unwanted modes. We use similar ridge waveguides as the HOM couplers of the ESRF-EBS monocell [3], with a cut-off frequency of 2.2 GHz. A campaign of simulation in GdfidL allowed to optimize the best position of the HOM couplers, one per cell is sufficient.

Referring to Table 1, the 2X5-Cell structure exceeds the LCBI threshold and is rejected for the final design. For a slot aperture of 23.5°, the longitudinal impedance of the 2x4-Cell structure is at the limits of the LCBI threshold, see Fig. 5(a). The two remaining structures, fully meet the stability criterion as shown in Figs. 5(b) and 5(c).



(a) Slot aperture 23.5°

(b) Slot aperture 25°

(c) Slot aperture 27.5°

Figure 5: Longitudinal impedance and LCBI threshold (black dashed line).

The LOM/HOM damping can be largely enhanced mixing two different structures of Table 1: the two spectra will be shifted in frequency and the resulting total impedance will be reduced w.r.t. twice the same spectrum. Even using the structure with slot aperture of 23.5° the total impedance is well below the threshold (see Fig. 6).

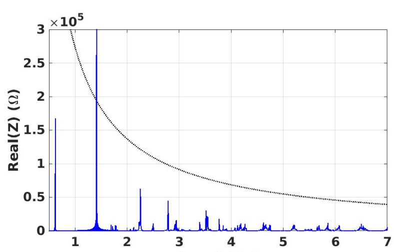
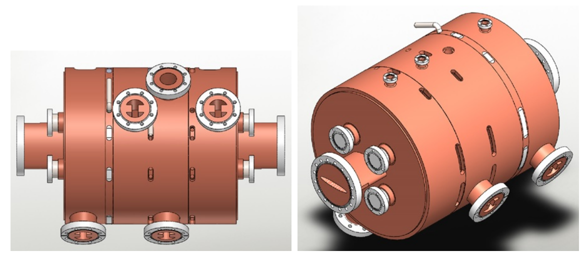


Figure 6: Impedance combination of structures with slot apertures of 23.5° and 25°. Black dashed line is the LCBI threshold.

ENGINEERING INTEGRATION

Figure 7 shows a preliminary 3D Model of a 4-Cell structure. This model already includes the cooling system, dimensioned to evacuate the heat-load induced by the power as from Table 1 and integrates the optimised positions of the LOM and HOM couplers.

At the present, the most critical point is the cooling of the LOM antennas. Indeed these antennas, unavoidably, couple a small portion of the TM020 which results in 160 W/antenna for the structure with a slot aperture of 23.5° and 110 W/antenna for 25°. This heat-load needs to be removed but the implementation of a cooling system is rather intricate considering the size of the antennas and their penetration inside the cavity. Studies are ongoing but also a parallel approach, using ferrite tiles placed at the node of the magnetic field, is under consideration. In this case the ferrites would not penetrate in the cavity.



(a) Side View

(b) Isometric View

Figure 7: 3D Model.

The auxiliaries need to be finalised. Preliminary studies on tuners have been already performed: two pistons (in cell 2 and 3) of 40 mm of diameter, with a stroke of 30 mm (-10 mm to +20 mm) provide for the required Δf=1 MHz needed to park the cavity. Also the impact on the impedance spectrum has been checked and validated. For RF power couplers we intend to use waveguide couplers. The HOM absorbers will be based on the experience of the monocell HOM damped cavity.

CONCLUSION

The design of a TM020 damped, multicell cavity is in an advanced stage. The electromagnetic design of the cavity, which includes the LOM/HOM damping and the impact of the tuners, is completed. The mechanical integration is following in parallel and a preliminary mechanical model is already available. The most critical point, at the present, is the cooling of the LOM antennas. Studies are ongoing and a parallel approach using ferrite tiles placed in correspondance of the node of the magnetic field of the TM020 is under consideration.

REFERENCES

[1] N. Yamamoto *et al.*, "Reduction and compensation of the transient beam loading effect in a double rf system of synchrotron light sources", *Phys. Rev. Accel. Beams*, vol. 21, no. 1, p. 012001, Jan. 2018. doi:10.1103/PhysRevAccelBeams.21.012001

[2] K. Bane and R. Gluckstern, "The Transverse wake field of a detuned x band accelerator structure", SLAC, Stanford, CA, Unites States, Rep. SLAC-PUB-5783, 1993.

[3] A. D'Elia, J. Jacob, and V. Serriere, "ESRF-EBS 352 MHz HOM Damped RF Cavities", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB333, this conference.