ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA132

BASIC HIGH-POWER DESIGN OF A 1.5-GHz TM020-TYPE HARMONIC CAVITY FOR THE KEK FUTURE LIGHT SOURCE*

T. Yamaguchi†, N. Yamamoto, D. Naito, T. Takahashi, S. Sakanaka
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

In the 4th-generation light sources, harmonic cavity for bunch-lengthening is an essential tool to mitigate the intrabeam scattering effect that is severe in ultimately-low emittance storage rings. For the use in a future light source at KEK, we have designed a normal-conducting third-harmonic cavity with a frequency of 1.5 GHz. In this cavity, the higher TM020 resonant mode is used as an accelerating mode. The basic electromagnetic and mechanical designs are presented.

BASIC CAVITY DESIGN

The TM020-type RF cavity [1, 2] was first proposed as a damped accelerating cavity for the SPring-8-II upgrade project. As shown in Fig. 1, coaxial slots are arranged at the magnetic node where the magnetic field of the accelerating mode is zero, and they are terminated by RF absorbers (ferrites). These slots can heavily damp most of the harmful parasitic modes, i.e., higher- and lower-order modes, other than the TM020 accelerating mode.

The TM020-type cavity has another advantage. The volume of this cavity is 4 – 5 times as large as those of fundamental TM010-type cavities, and it can store larger electromagnetic energy. Thanks to this feature, the transient beam-loading effects caused by non-uniform filling of electron bunches can be reduced. This is crucially important for the harmonic cavity because the transient RF variation degrades the bunch-lengthening performance.

Because of such advantages of the TM020-type cavity, we have conducted the design study of the TM020-type harmonic cavity for a KEK future light source project. In our design study, we have assumed storage-ring parameters [3, 4] of a 3-GeV 4th-generation light source with circumference of 571 m.

Because of the long radiation damping times of 23 ms and 38 ms (without insertion devices) in the longitudinal and vertical directions, respectively, together with high beam current of 500 mA, the requirement on the parasitic-mode damping performance to the harmonic cavity is stringent. The upper limits of the coupling impedances per harmonic cavity, which are needed to avoid coupled-bunch instabilities, are $\omega/(2\pi)\cdot\mathrm{Re}[Z(\omega)] < 2.4$ kΩ·GHz in the longitudinal direction and $\mathrm{Re}[Z_T(\omega)] < 23$ kΩ/m in the transverse direction, respectively. Then, we intensively improved the parasitic-mode damping performance in the design study.

In addition to this, we studied an issue of the Q-factor reduction in the accelerating mode, which is caused by the parasitic-mode damper. This phenomenon occurs when the axial-symmetry of the cavity inner shape is violated. In our design study, we found a solution to cure this issue.

Optimized Inner Shape for Improving Parasitic-mode Damping Performance

In our initial study of parasitic-mode damping, there was a difficulty that the parasitic modes, whose magnetic nodes located close to that of the accelerating mode, could not be damped well. Using the electromagnetic simulation software, CST Studio Suites, we optimized the cavity inner shape so as to effectively damp them. The detailed optimization process is described in [5, 6].

Figure 1 shows the final design of the inner shape with the field patterns of the accelerating mode. The diameter of the beam pipe is 52 mm, which is approximately twice as large as that of the typical beam duct of the assumed storage ring [4]. This large diameter is effective to propagate the higher-order modes into the beam ports. The cut-off frequencies of the TE11 and TM01 propagating modes of the beam pipe are 3.38 GHz and 4.41 GHz, respectively. The length of the cavity (78 mm) was chosen to be relatively short so as to reduce the number of higher-order modes with the frequencies below the cut-off frequencies of the beam pipe. The curvature radius (R39 mm) of the cavity equator and the shape of the nose cone were optimized to achieve the maximum damping of the harmful parasitic modes [5, 6]. Additionally, comparing the previous design presented in [5], we changed the shape in the termination of the coaxial slots, as shown in Fig. 2. By this change, we could increase the volume of the installable RF absorbers by a factor of 2.3 and succeeded in reducing the power density of the absorbed RF [6].

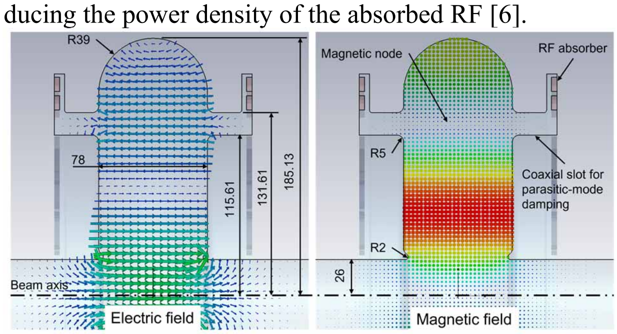

Figure 1: Inner shape of the TM020-type harmonic cavity together with the field patterns of the accelerating mode.

The coupling impedances were calculated using both the Wakefield and Eigenmode Solvers of the CST Studio. We assumed the property of the ferrite HF70 from TDK

* Work supported by JST SPRING Grant Number JPMJSP2104 and JSPS KAKENHI Grant Numbers JP17K05131 and JP20H04459.
† yamaguc@post.kek.jp

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA132

Corp. [7] for RF absorbers. We assumed to install 72 ferrite blocks, with dimension of 25.5 × 10.26 × 4 mm each. The calculated coupling impedances are shown in Fig. 3. The impedances of most parasitic modes are within the target values, whereas those of several modes exceeded the upper limits. In the longitudinal plane, the peaks at 4.8 and 5.5 GHz are approximately two times as high as the upper limit. In the transverse plane, the highest peak associated with the TE121 mode is approximately 10 times as high as the upper limit. Estimated growth rates of the coupled-bunch instabilities due to the impedances of these peaks are 90 and 300 s^{-1} in the longitudinal and transverse planes, respectively. We believe that the coupled-bunch instabilities with these growth rates can be managed by bunch-by-bunch feedback systems.

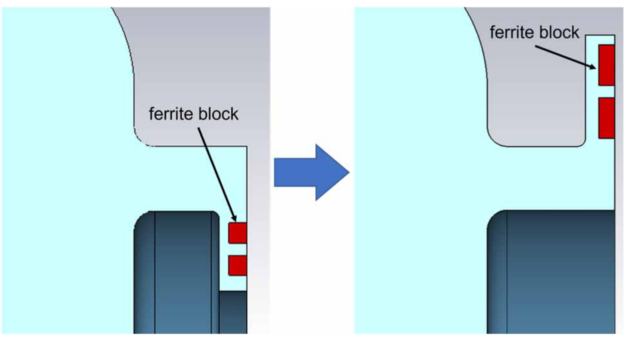

Figure 2: Termination of the coaxial slot (a) before and (b) after the design improvement.

An Issue of the Q-reduction in the Accelerating Mode and its Cure

With the coaxial damping structure of the TM020-type cavity, the power of the accelerating mode can partially leak into the coaxial slots when the components such as a frequency tuner and an input coupler are mounted. This is caused by a deformation of the accelerating field due to perturbation. Subsequently, a large power loss that is

Table 1: Parameters of the Accelerating Mode

Parameter	**Value**
Frequency [$\omega_{res}/(2\pi)$]	1.500 GHz (3rd harmonic)
R_{sh}/Q_0 [= $V_c^2/(\omega_{res} W)$]	68.0 Ω/cav.
Unloaded Q ($Q_0 = \omega_{res} W/P_c$)	31,400
Shunt impedance ($R_{sh} = V_c^2/P_c$)	2.14 Ω/cavity
Harmonic RF voltage (V_c)	155.4 kV/cavity
Wall-loss power (P_c)**	11.3 kW/cavity
Coupling coefficient	0.5
Max. wall-loss density**	11.0 W/cm^2
Max. electric field**	6.7 MV/m

* *W* is the electromagnetic stored energy.

** Values provided at V_c = 155.4 kV/cavity

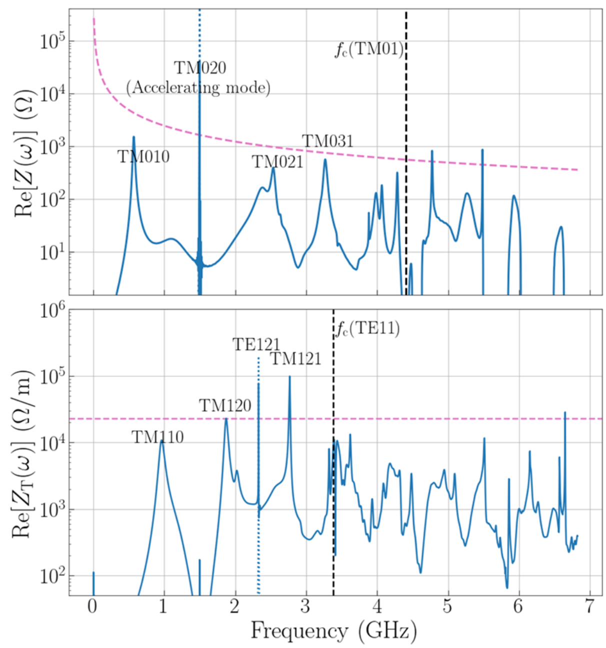

Figure 3: Real parts of the coupling impedances. The blue solid and dashed lines show the impedances calculated with Wakefield and Eigenmode Solvers, respectively. The magenta dashed lines show the targeted upper limits of the impedances. The vertical dashed lines indicate the cut-off frequencies of the TM01 and TE11 modes in the beam pipe, respectively.

comparable to the wall-loss power (~11 kW) can be produced [6] in extreme cases. Such a large power loss can damage the RF absorbers, and should be avoided.

In our design study [6], we found that improving the rotational symmetry of the cavity shape is essential to minimize the loss of the accelerating mode in the absorbers. To this end, we arranged three frequency tuners with three-fold rotational symmetry as shown in Fig. 4.

For an input coupler, we devised a coupling loop which imposes minimum perturbation to the accelerating mode. As shown in Fig. 4 (right), we tapered an input coaxial line, and placed a small coupling loop at its end.

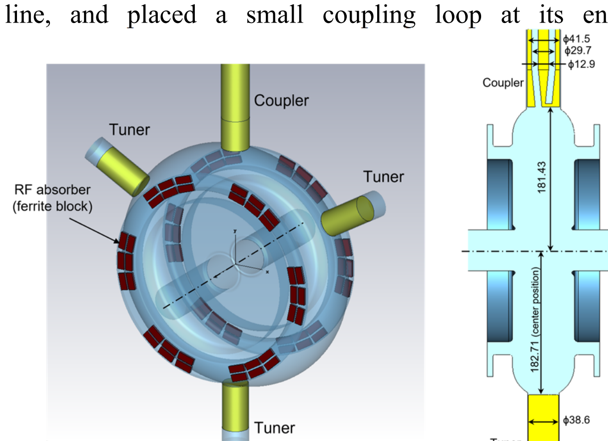

Figure 4: Inner structure of the cavity with the three frequency tuners, an input coupler, and ferrite blocks.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA132

With the design shown in Fig. 4, the losses in the absorbers could be kept within 1% of the total wall loss even when the resonant frequency was adjusted in the range of ±500 kHz. The parameters of the accelerating mode in the final design are shown in Table 1.

MECHANICAL DESIGN

Cavity Structure

After the electromagnetic design was fixed, we studied a mechanical design for the high-power model. The three-dimensional computer-aided design (3D-CAD) image is shown in Fig. 5. Blown- and gray-colored components are made of OFHC (oxygen-free high-conductivity copper) and SS (stainless steel), respectively. The cavity is composed of a main part, end plates, and bridge plates. The end plate and bridge plate are joined by brazing. This end-plate assembly is attached to the main part by bolts where the vacuum is sealed using metal O-rings. In each bridge plate, six sector-shaped openings are placed in order to install absorber modules shown in Fig. 6(a). In an absorber module, six ferrite blocks are bonded on a copper base.

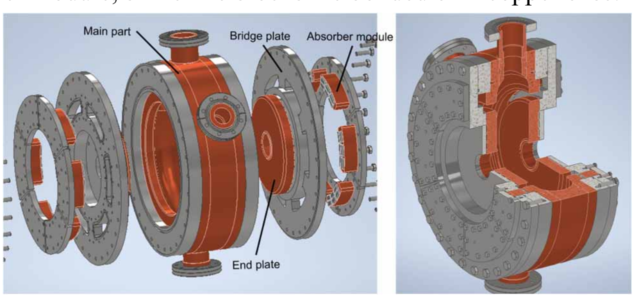

Figure 5: 3D-CAD image of the mechanical design.

Thermal and Structural Analyses

To confirm the mechanical robustness of the structure shown in Fig. 5 at high-power operation, we conducted thermal and structural analyses using the ANSYS software. Total dissipated power of 11 kW, which corresponds to the RF voltage of 155 kV/cavity, was assumed. For cooling water, we assumed the inlet temperature of 20°C and flow rate of 8.1 L/min (average flow velocity 2.5 – 3.0 m/s). In this setting, the heat transfer coefficients on water channels were estimated 1.0 – 1.3 W/(cm^2 K).

Figures 7(a) and (b) show the simulated temperature and von-Mises stress distributions, respectively. In Fig. 7(b), the deformation of cavity structure is also displayed. The maximum stress was 33 MPa at the SS part of the end plate, which is sufficiently smaller than the yield strength of SS. The maximum deformation of the inner shape was 25 μm on the equator. Using the simulated deformations, the change in the resonant frequency was estimated to be approximately −210 kHz; this is well within the variable range (±500 kHz) with the frequency tuners.

We also conducted the analyses on an absorber module. We assumed absorbed power density of 7 – 15 W/cm^3 in the ferrites, where the density depends on the position in the blocks. These values indicate the sum of the power losses from the accelerating mode and the parasitic-mode loss. The simulated temperature and von-Mises stress distributions are shown in Fig. 6. The maximum temperature is 55°C; this is well within the Curie temperature (> 100°C [7]) of HF70 ferrite. On the bonding surface between the ferrite blocks and the copper plate, the von-Mises stress is approximately 6 MPa, which is less than 30% of the tensile strength of the Ni-Zn ferrite [8]. Hence, we confirmed that the absorbed power in the ferrite blocks were permissible.

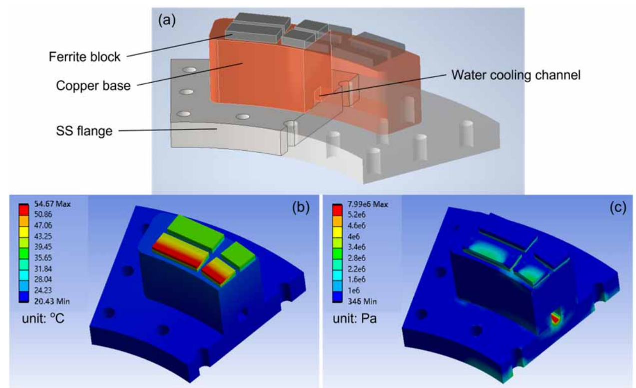

Figure 6: (a) The mechanical structure of the absorber module where the half is shown transparently, (b) the simulated temperature distribution, and (c) the von-Mises stress distribution.

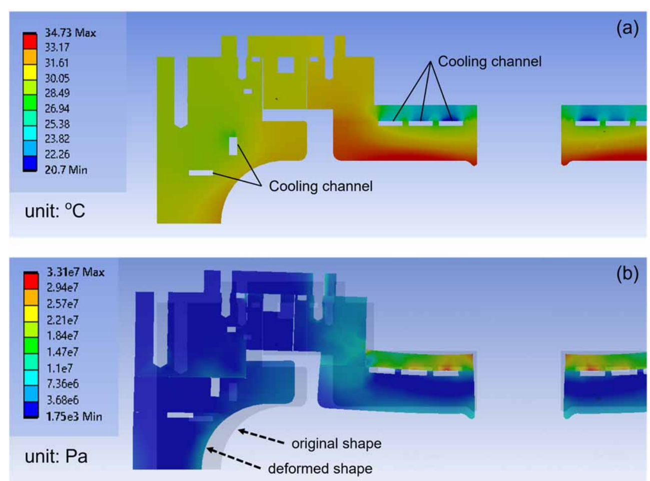

Figure 7: (a) Simulated temperature distribution and (b) von-Mises stress distribution. The deformation was exaggerated by a factor of 500.

CONCLUSION

We have designed the TM020-type harmonic cavity for KEK future light source. In this study, we achieved an electromagnetic design which satisfies excellent parasitic-mode damping performance as well as minimum power loss of the accelerating mode in the RF absorbers. We designed the mechanical structure of a high-power model, and confirmed that it is mechanically robust under the wall losses of up to 11 kW. In the near future, we plan to fabricate a high-power model for the use in the Photon Factory 2.5-GeV storage ring at KEK.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-WEPA132

REFERENCES

[1] H. Ego, J. Watanabe, S. Kimura, K. Sato, "Design of a HOM-damped RF cavity for the SPring-8-II storage ring", in *Proc. the 11th Annual Meeting of Particle Accelerator Society of Japan (PASJ2014)*, Aomori, Japan, 2014, p. 237 (in Japanese).

[2] H. Ego, T. Inagaki, T. Oshima, N. Shigeoka, T. Sugano, H. Hara, S. Miura, "High power test of the prototype HOM-damped RF cavity for the SPring-8-II storage ring", in *Proc. the 16th Annual Meeting of Particle Accelerator Conference of Japan (PASJ2019)*, Kyoto, Japan, 2019, p. 17 (in Japanese).

[3] K. Harada, T. Honda, Y. Kobayashi, N. Nakamura, K. Oide, H. R. Sakai, S. Sakanaka, M. Adachi, K. Tsuchiya, N. Funamori, "The HMBA lattice optimization for the new 3 GeV light source", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, p. 3251-3253. `doi:10.18429/JACoW-IPAC2016-THPMB012`

[4] KEK Light Source, Conceptual Design Report, ver. 1.1, 2017, `https://www2.kek.jp/imss/notice/assets/2017/05/22/KEKLS_CDR_170522.pdf`

[5] T. Yamaguchi, S. Sakanaka, N. Yamamoto, D. Naito, T. Takahashi, "Optimization of the parasitic-mode damping on the 1.5 GHz TM020-type harmonic cavity", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, SP, Brazil, May 2021, pp. 1064-1067. `doi:10.18429/JACoW-IPAC2021-MOPAB343`

[6] T. Yamaguchi, N. Yamamoto, D. Naito, T. Takahashi, S. Sakanaka, "Design and low-power measurement of 1.5-GHz TM020-type harmonic cavity for KEK future synchrotron light source", submitted to *Nucl. Instrum. Methods Phys. Res. A*., to be published.

[7] S. Ito, "Basics of ferrite and noise countermeasures", TDK EMC Technology; TDK Corp. Tokyo, 2011.

[8] Soft Ferrites, Pretrial, Ltd.; `https://www.proterial.com/e/products/elec/tel/p13_21.html`