A Novel Bimodal Radio-frequency Cavity with Independent Tuning and Effective Higher-Order Mode Damping for Advanced Synchrotron Light Sources

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Date: 2025-04-28T10:48:28+00:00

Abstract

Double radio-frequency (RF) systems, comprising both fundamental and harmonic cavities, are essential in advanced synchrotron light sources for lengthening beam bunches, thereby increasing the Touschek lifetime and reducing intrabeam scattering. RF cavities must incorporate effective higher-order mode (HOM) damping to mitigate coupled bunch instabilities (CBI). Additionally, a compact design is crucial for fitting within the limited straight sections of storage rings. This paper presents a novel coaxial bimodal cavity that simultaneously delivers fundamental and harmonic voltages, allowing independent operation of both modes and effective HOM damping. It offers a more compact and efficient alternative to conventional separate cavities. A prototype cavity design was developed, featuring resonant frequencies of 166.6 MHz for the fundamental mode and 499.8 MHz for the third harmonic mode. Simulation results indicate the successful implementation of a bimodal RF cavity, featuring independent frequency tuning, separate RF drives, and effective HOM damping. This work offers a compact and efficient solution for implementing double-frequency RF systems in advanced synchrotron light sources.

Full Text

Preamble

A Novel Bimodal Radio-frequency Cavity Enabling Independent Tuning and Effective Higher-Order Mode Damping for Advanced Synchrotron Light Sources

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Double radio-frequency (RF) systems, comprising both fundamental and harmonic cavities, are essential in advanced synchrotron light sources for lengthening beam bunches, thereby increasing the Touschek lifetime and reducing intrabeam scattering. RF cavities must incorporate effective higher-order mode (HOM) damping to mitigate coupled bunch instabilities (CBI). In addition, a compact design is crucial for fitting within the limited straight sections of the storage rings. This paper presents a novel coaxial bimodal cavity that simultaneously delivers fundamental and harmonic voltages, allowing independent operation of both modes and effective HOM damping. It offers a more compact and efficient alternative to conventional separate cavities. A prototype cavity design was developed, featuring resonant frequencies of 166.6 MHz for the fundamental mode and 499.8 MHz for the third-harmonic mode. Simulation results indicate the successful implementation of a bimodal RF cavity, featuring independent frequency tuning, separate RF drives, and effective HOM damping. This work offers a compact and efficient solution for implementing double-frequency RF systems in advanced synchrotron light sources.

Keywords: Bimodal RF cavity, Independent tuning, Higher-Order Mode Damping, Synchrotron light sources

∗ This work was Supported by National Natural Science Foundation of China (No. 12205168)

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INTRODUCTION

Double radio-frequency (RF) systems, which consist of both fundamental and harmonic cavities, have successfully increased Touschek lifetimes by lengthening beam bunches in several third-generation light sources [1–4]. Currently, fourth-generation synchrotron radiation (SR) sources aim to achieve horizontal beam emittances of approximately 100 pm rad or lower and are under construction or active design worldwide [5]. In these ultralow-emittance storage rings, challenges such as emittance growth due to intrabeam scattering and short Touschek lifetimes become serious concerns, particularly in the low-to-medium energy range [6]. To mitigate these adverse effects, the implementation of double RF systems has become essential in nearly all fourth-generation storage rings.

Many devices, including magnets, RF cavities, and beam position monitors, need to be installed in the storage ring. To maximize the light source's utilization efficiency, it is crucial to install as many insertion devices as possible, making the straight sections of the storage ring particularly valuable.

The use of separate fundamental and harmonic cavities simplifies operations in a double RF system but requires multiple cavities, especially for normal conducting (NC) systems, due to limitations such as cavity wall dissipation and the limited capacity of power input couplers [7–9]. The innovative bimodal cavity, which integrates both fundamental and harmonic modes, can reduce the required number of RF cavities, offering space efficiency and economic advantages. Reducing the number of cavities can also decrease beam impedance, improving beam quality and stability. Additionally, employing uniform cavity types simplifies maintenance and enhances system stability.

Bimodal cavities have been proposed to enhance the performance of RF electron guns by providing a flat-top-like RF profile [10, 11], yielding excellent results. These bimodal cavities are specifically designed to operate in TM010 + TM011, TM012, TM020 or TM030 modes by modifying the shape of pillbox or elliptical cavities. A similar bimodal cavity design has also been proposed for synchrotron light sources [12]. Despite the straightforward concept, bimodal cavities present significant challenges, particularly in achieving independent frequency tuning and efficient higher-order mode (HOM) damping. Existing bimodal RF cavities struggle to address these issues, limiting their application, particularly in synchrotron radiation light sources with high-brightness beams.

To meet the stringent requirements of advanced synchrotron radiation light sources, we propose a novel coaxial bimodal cavity design. This structure utilizes its two lowest monopole modes for the fundamental and third harmonic systems, respectively. The distinct spatial distributions of the electromagnetic fields in these modes enable independent frequency tuning. Additionally, the HOMs with high impedance exhibit frequencies above those of the accelerating modes, allowing for effective damping. Furthermore, the coaxial bimodal cavity is ideally suited for low-frequency RF systems that facilitate achieving ultra-low emittances in synchrotron light sources via on-axis injection [13].

In this paper, we introduce the principles of the coaxial bimodal cavity, outline its design requirements, and present a specific prototype design tailored to the South China Advanced Photon Source (SAPS), a fourth-generation light source, planned for construction in China [15]. The main parameters and RF requirements of the storage ring are shown in Table 1 . However, practical RF cavity designs require a larger accelerating gap to achieve voltages of several hundred kilovolts or more, which results in a very small value of Cgap. Solving Eq. (1) illustrates the relationship between f0, f1, and the ratio f1/f0 with respect to Cgap, as depicted in Fig. 1 Figure 1: see original paper, where Z0 is 100 Ω. It is readily observed that reducing Cgap results in a narrower frequency gap between the two modes, falling below the initial 1:3 frequency ratio.

In the conventional scheme, eight 166.6 MHz HOM-damped cavities are planned for the fundamental system and two active 499.8 MHz HOM-damped cavities for the harmonic system. We propose using three bimodal cavities (BC) to replace the existing three fundamental cavities (FC) and two harmonic cavities (HC). The paper is organized as follows: Section II outlines the principles and design requirements of the coaxial bimodal cavity. Section III presents a comprehensive design of a bimodal cavity prototype, including RF design, multipacting analysis, dual-frequency tuning, dual-power coupling, HOM damping, and thermomechanical simulations. The conclusions are summarized in Section IV.

TABLE 1. Main parameters and RF requirements of the SAPS storage ring.

CONCEPT OF COAXIAL BIMODAL CAVITY

In an ideal quarter-wave coaxial RF cavity, the length of the accelerating gap is negligible compared to the cavity length, and the resonant frequencies can be calculated using Equations (1) and (2) [16].

(cid:40)Z0 tan (2πfnL/c) = 1/(2πfnCgap)
Z0 = (cid:112)µ/ 2π log (r2/r1)

Where Z0 denotes the characteristic impedance, n represents the serial number of the resonant mode, fn is the resonant frequency, L is the cavity length, c is the speed of light, Cgap is the capacitance of the accelerating gap, and r1 and r2 are the radii of the inner and outer conductors, respectively.

Here, µ and represent the permeability and permittivity in vacuum, respectively. According to Eq. (1), when the Cgap is small, the resonant frequencies of HOMs induced by a coaxial structure can be approximated by fn = (2n + 1)c/(4L) (n = 0, 1, 2, . . .).

The electromagnetic field distribution of these modes at the acceleration gap exhibits monopole characteristics. Consequently, the first two modes, denoted as M0 and M1, have a frequency ratio of 1:3, making them suitable for application as fundamental and third harmonic modes, respectively.

Fig. 1. (Color online) (a) f0, f1 and f0/f1 as the function of Cgap when Z0 is 100 Ω. (b) Graphical solution of transcendental Equation (1).

Graphical solutions to transcendental Equation (1) illustrate that an increase in the capacitance (Cgap) leads to a notable decrease in the fundamental frequency (f0), while exerting minimal influence on the first harmonic frequency (f1), as demonstrated in Fig. 1(b). Intersection points A and B, where curve y intersects with curve y1, correspond to the solutions for f0 and f1, respectively. These points shift to positions C and D when Cgap increases tenfold. Therefore, a capacitor-loaded plate, as shown in Fig. 2 Figure 2: see original paper, can be utilized to adjust their frequency relationship by increasing the capacitance Cgap. This method has been successfully implemented in the 100 MHz RF cavity of the MAX IV facility, enabling the frequency of the first HOM to be increased to four times or more than the fundamental frequency [17]. Additionally, as illustrated in Fig. 2(b), modifying the outer conductor diameter in the accelerating gap region alters the electromagnetic field intensity within the gap, thereby adjusting the Cgap value. Consequently, the two methods of altering Cgap can be employed to design a bimodal cavity with both fundamental and third harmonic modes.

Fig. 2. (Color online) Two potential schemes for the bimodal cavity. (a) Scheme 1 by utilizing a capacitor loaded plate. (b) Scheme 2 by modifying the outer conductor diameter of the accelerating gap region.

In the double RF system of advanced synchrotron light sources, which is used to lengthen the beam bunch and consists of a fundamental cavity and a high-order harmonic cavity, the voltage can be written as [3]:

$V(z) = Vrf \sin(\omega rfz/c+\Phi s)+kVrf \sin(n\omega rfz/c+n\Phi h)$, (3)

where Vrf is the fundamental RF voltage, ωrf is the fundamental frequency, z is the longitudinal coordinate of the electron, k is the relative harmonic voltage to the fundamental RF voltage, Φs is the synchronous phase, Φh is the relative harmonic phase, and n is the harmonic number. To lengthen beam bunches, the harmonic amplitude and phase should be adjusted to cancel the slope of the fundamental RF voltage at the bunch center. The harmonic voltage and phase at this condition are given by

(cid:113) $1/n2 - (U0/Vrf)2/(n2 - 1)$
$\tan(n\ h) = nU0/Vrf$ / (cid:113) $(n2 - 1)2 - (nU0/Vrf)2$

where U0 is the energy loss per turn. In a bimodal cavity, the electric fields of both fundamental and harmonic modes exist simultaneously and share the same accelerating gap. Considering the Transit Time Factor (TTF) [18], the voltage gained by the electrons traveling close to the speed of light as they pass through the bimodal cavity can be expressed as:

$V(z) = V1T1 \sin(\omega rf/cz + \ 1) + VnTn \sin(n\omega rf/cz + \ n)$
$T1 = \sin(\omega rf\ d/(2c))\ 2c/(\omega rf\ d)$
$Tn = \sin(n\omega rf\ d/(2c))\ 2c/(n\omega rf\ d)$

where V1 and Vn are the voltage amplitudes of the fundamental and harmonic modes, respectively; T1 and Tn are the Transit Time Factors for the fundamental and harmonic modes; 1 and n are the phases with respect to the fundamental and harmonic voltages; and d is the length of the accelerating gap.

The relationship between the Transit Time Factors of the fundamental and third harmonic modes and the acceleration gap length in a bimodal cavity is shown in Fig. 3 [Figure 3: see original paper]. The transit time factors decrease significantly with an increasing acceleration gap, especially in the harmonic mode. Coaxial bimodal cavities have a short accelerating gap, less than half of the wavelength for both fundamental and harmonic modes, resulting in high acceleration efficiency.

Fig. 3. (Color online) Transit Time Factors of the fundamental and harmonic modes as functions of the acceleration gap length in a bimodal cavity. The horizontal axis represents the length of the acceleration gap, in units of the fundamental wavelength, and the harmonic mode is of order (n = 3).

The primary challenge for bimodal cavities in synchrotron light sources is achieving independent tuning of the two operating modes. Variations in Cgap significantly affect f0, whereas their impact on f1 is negligible, as shown in Fig. 1(a). This enables the implementation of an independent tuning system for the fundamental mode by adjusting Cgap via squeezing the ‘end plate’, a plate adjacent to the accelerating gap. Additionally, in coaxial bimodal cavities, a significant difference in electromagnetic energy density distribution between the two modes near the outer conductor is observed, as illustrated in Fig. 4 [Figure 4: see original paper]. Specifically, the M1 mode exhibits a pronounced magnetic field and a diminished electric field near the ‘end plate’, whereas the M0 mode displays a comparatively uniform electromagnetic field. A plunger-type tuner can be utilized in this region to fine-tune f1 with negligible influence on f0, by leveraging the principles of cavity perturbation theory as delineated in Equation (6) [16]:

(cid:82) (cid:82) (µ0|H|2 − 0|E|2) dV
(µ0|H|2 + 0|E|2) dV

where V1 and V0 denote the volumes of the perturbation and the cavity, respectively. Thus, two independent tuning systems for the respective operating modes within the bimodal cavity can be achieved.

Fig. 4. (Color online) Electromagnetic energy density distribution for two modes adjacent to the cavity’s outer conductor in the axial direction, each with 1 J of stored energy, where z = 50 mm represents the end plate. E0 and H0 denote the electric and magnetic field values of the fundamental mode, respectively, while E1 and H1 denote those of the harmonic mode.

In advanced synchrotron light sources, many harmonic cavities operate passively, with the harmonic RF voltages induced by the beam itself [19, 20]. However, specific requirements, such as varying beam currents for different operational modes and specific injection schemes, necessitate an active harmonic system in certain facilities, including HEPS [21] and PETRA IV [7]. In these cases, the bimodal cavity requires two input couplers to facilitate active operation for both systems. To avoid mutual interference, these input couplers must be designed with narrow bandwidths of less than tens of MHz. Additionally, HOM damping is crucial for RF cavities in advanced light sources. The coaxial bimodal cavity utilizes the first two monopole modes as accelerating modes, and there are no high-impedance HOMs between them. Waveguide-type couplers (e.g., BESSY 500 MHz HOM-damped cavity [28]), antenna-type HOM absorbers (e.g., MAX4 cavities [30]), and beam-type absorber [14] can be used to suppress these HOMs.

With this concept, we designed a coaxial bimodal RF cavity for advanced synchrotron light sources. The specific design objective is to meet the practical application requirements of the SAPS. The detailed design of this bimodal cavity is presented in the following sections.

PROTOTYPE DESIGN OF A BIMODAL CAVITY

A. RF Design

The bimodal cavity was designed with fundamental and third harmonic frequencies of 166.6 MHz and 499.8 MHz, respectively. Several constraints were considered in the design process. First, to ensure practicality, the outer conductor diameter and length were kept below 0.8 m and 0.5 m, respectively. Second, the frequencies for the fundamental and third harmonic modes, corresponding to the two lowest monopole modes of the cavity, were set at 166.6 MHz and 499.8 MHz. This design aims to maximize their shunt impedances to ensure that the total cavity wall losses are less than 40 kW at the design voltages (V1 = 320 kV and V3 = 200 kV), reserving some margin for SAPS normal operation. Third, to enable effective HOM damping, the frequency of the next monopole mode with high impedance should exceed 600 MHz, ensuring a significant frequency separation from the operating modes.

Fig. 5 [Figure 5: see original paper]. (Color online) 3D RF model of the bimodal cavity: (a) Scheme 1, featuring a capacitor-loaded plate; (b) Scheme 2, characterized by a modified outer conductor diameter.

The design and optimization of the two schemes outlined in Section II were performed using CST Microwave Studio [23], and the RF simulation models are illustrated in Fig. 5. A 30 mm thick space is engineered between the beam pipe and the inner conductor to house cooling pipes, with the cavity's beam pipe having a diameter of 63 mm. For the extraction of HOMs, an enlarged tube is strategically positioned outside the cavity. The main parameters of the schemes are listed in Table 2 .

Fig. 6 [Figure 6: see original paper]. (Color online) Electric field distributions with 1 J of stored energy. (a) Electric field distribution for mode M0. (b) Electric field distribution for mode M1. (c) Electric fields along the beam passage.

The electric field distributions of the two operating modes, each with 1 J of stored energy, are depicted in Fig. 6(a) and 6(b). Additionally, the profile of the longitudinal electric field for beam acceleration is presented in Fig. 6(c), where z = 85 mm denotes the center of the accelerating gap. The optimized shunt impedances for the two modes are 5.71 MΩ and 1.83 MΩ, respectively.

B. Multipacting

The multipacting (MP) simulation of the bimodal cavity was conducted using CST Particle Studio and CST Microwave Studio [23]. The argon-discharged copper equivalent to the copper material after high power conditioning [24] was chosen for the cavity's metallic walls. To expedite computations and accurately identify multipacting locations, the cavity's inner surface was divided into several initial particle source regions. The particle sources provided simulations with primary electrons uniformly distributed across the source area and over an energy range of 0–4 eV. The RF electromagnetic field map for both fundamental and harmonic modes, calculated via the eigenmode solver, was imported into the Particle-in-Cell (PIC) solver. Simulations were conducted over twelve RF phases (in 30° increments) and accelerating voltages from 25 kV to 750 kV, tracking particle dynamics over 100 RF periods to ensure steady-state convergence. Emission and collision data from each surface were analyzed to compute the integral secondary emission yield (SEY = Total Secondaries/Total Impacts) [25]. As depicted in Figure 7 [Figure 7: see original paper], the maximum SEY for all regions of the fundamental, harmonic, and combined modes consistently remained below the critical threshold of 1.0, indicating the absence of multipacting when the cavity's inner surface is adequately treated.

Fig. 7. (Color online) The maximum SEY for all regions of the fundamental, harmonic, and combined modes of the bimodal cavity after high power conditioning, as simulated by using argon-discharged copper.

TABLE 2. Two options for the bimodal cavity. The impedances and quality factors of the modes in Scheme 2 surpass those in Scheme 1, primarily due to the increased cavity loss from the capacitor-loaded plate. The subsequent design was based on Scheme 2.

Parameter	Scheme 1	Scheme 2
Frequency (MHz)	M0: 166.6, M1: 499.8	M0: 166.6, M1: 499.8
Shunt impedance Rsh (MΩ)	(values not specified)	(values not specified)
Quality Q	(values not specified)	(values not specified)
R/Q (Ω)	(values not specified)	(values not specified)
Cavity length (mm)	(values not specified)	(values not specified)
Cavity diameter (mm)	(values not specified)	(values not specified)
Accelerating gap length (mm)	(values not specified)	(values not specified)

C. Dual-frequency Tuning

Following the methodology detailed in Section 2, we developed two distinct tuning systems for the bimodal cavity. The fundamental mode tuning is achieved by mechanically squeezing the end plate as illustrated in Fig. 8 Figure 8: see original paper. To minimize effects on the harmonic frequency, precise design of the end plate deformation was necessary, employing cavity perturbation theory and accounting for the electromagnetic field distribution in this area. Figure 8(b) shows the radial distribution of electric and magnetic field energy densities for both operating modes near the end plate. Analysis reveals that the electric field energy of the fundamental mode (M0) in the radial span of 70–188 mm—excluding the 0–70 mm range designated for beam tubes—vastly surpasses the magnetic field energy. In contrast, the electric and magnetic field energies of the third harmonic (M1) are comparable. Consequently, an end plate, designed with a minimum thickness of 5 mm at a radius of 188 mm, aims to enable controlled deformation while ensuring mechanical strength through the tuning mechanism, allowing for independent tuning of the fundamental mode. The achieved frequency tuning range for the fundamental mode is 500 kHz, with an end plate deformation of $±$1 mm under a maximum stress of 68.6 MPa. Simulation results from CST multiphysics calculations indicate tuning sensitivities of 252 kHz/mm for the fundamental mode and 1.3 kHz/mm for the third harmonic mode, as illustrated in Fig. 9 Figure 9: see original paper. The impact of fundamental mode tuning on the third harmonic frequency is 0.5%, compared to the initial estimate of 0.1% derived from preliminary calculations (Eq. 6) that assumed uniform end plate displacements.

Fig. 8. (Color online) (a) Frequency tuning mechanisms. The fundamental frequency is tuned by axially compressing the end plate, and a minimum thickness of 5 mm at a radius of 188 mm was designed to control the location of deformation. The harmonic frequency is tuned by employing a tuner plunger. (b) Radial energy density distribution for two operating modes near the end plate, each with 1 J of stored energy.

The frequency of the harmonic mode is adjusted by employing a tuner plunger, which has a diameter of 120 mm, as illustrated in Fig. 8(a), strategically positioned at a location where the third harmonic exhibits a strong magnetic field and a weak electric field, while the distribution of the fundamental electromagnetic field remains relatively uniform, as illustrated in Fig. 4. The tuner has a travel range of 40 mm (−20 mm to +20 mm), with a maximum insertion depth into the cavity of 20 mm. The simulation results indicate that the tuning range for the third harmonic is $±$500 kHz, with tuning sensitivities of approximately 25.6 kHz/mm for the third harmonic mode and 0.7 kHz/mm for the fundamental mode, as illustrated in Fig. 9 Figure 9: see original paper. The impact of harmonic tuning on the fundamental frequency is less than 2%, which is sufficient to meet the requirements for independent tuning of bimodal cavities. This is because the normal conducting RF cavity has a bandwidth of several kHz, and the frequency change due to temperature shifts (after reaching thermal equilibrium) and beam loading is typically within a few kHz. It should be noted that during the initial stage of powering the cavity, the maximum frequency shift caused by changes in cavity temperature can reach up to 100 kHz. In such cases, both the fundamental and harmonic tuners need to be adjusted simultaneously. Additionally, since designing a choke structure for the two operating modes is challenging, spring fingers are installed near the inner wall of the ports to reduce the electromagnetic field entering the tuner. When the tuner is inserted 20 mm into the cavity, the power of the fundamental and third harmonic modes entering the tuner is approximately 90 W and 175 W, respectively, under normal operation. A water cooling system with a flow rate of 1.0 L/min is necessary to ensure that the temperature rise of the tuner does not exceed 15°C during operation.

Fig. 9. (Color online) Simulation results of the two tuning devices. (a) Variation in operating frequencies due to deformation of the end plate. (b) Variation in operating frequencies as a function of plunger insertion depth.

D. Dual-power Coupling

In this study, we designed two input power couplers to enable a double active RF system. The input power coupler for the fundamental mode was designed with a structure similar to the one developed for the 500 MHz/5-cell copper cavity [26], as depicted in Fig. 10 Figure 10: see original paper. To prevent mutual interference between the modes, it was engineered with narrow bandwidths of less than tens of MHz by incorporating a T-piece as a filter. This T-piece, featuring an electrical short in one arm, allows for optimization of RF performance by adjusting the electrical length of the short circuit. Additionally, water cooling is integrated with the high-power coupler's inner conductor to manage thermal loads. As illustrated by its S11 scattering parameters in Fig. 10(b), the coupler exhibits excellent transmission characteristics at the fundamental frequency, but approaches total reflection at the third harmonic frequency, demonstrating the fundamental input coupler's negligible impact on the third harmonic mode. To handle a power capacity greater than 125 kW, both the ceramic window and the inner conductor are water-cooled. Additionally, the ceramic window is coated with Titanium Nitride (TiN) to suppress multipacting.

Fig. 10. (Color online) (a) Cross-sectional view of the fundamental coupler. (b) S11 of the 166.6 MHz coupler.

The power of the third harmonic mode is delivered through a WR-1500 waveguide coupler, illustrated in Fig. 11 Figure 11: see original paper. The input coupler port is rectangular, measuring 381 mm by 190.5 mm, and incorporates a rectangular iris measuring 160 mm by 40 mm in the cavity's common wall. To accommodate different beam currents, the power coupling coefficient is adjustable between 1.0 and 5.0 by altering the length of the coupling tuner post, which has a diameter of 70 mm and is positioned 70 mm above the coupling slot [27]. The S21 parameters of the coupler, as shown in Fig. 11(b), indicate its ability to block the transmission of fundamental power while allowing effective propagation of third harmonic power. As a result, the two input couplers, each designed for a specific operating mode, can independently transmit power to the cavity without interference.

Fig. 11. (Color online) S21 parameters of the 499.8 MHz coupler for coupling coefficients $\beta = 1.0$ and $\beta = 2.1$.

E. HOM Damping

In this study, to achieve stronger HOM damping, we adopted a beam absorber. This approach is rarely used in normal-conducting (NC) cavities due to its significant impact on accelerating modes. However, in a coaxial resonator cavity, the impedance is primarily determined by the inner and outer radii and length, with negligible influence from enlarging the external beam tube. Consequently, a beam absorber can be used in NC coaxial cavities to effectively damp HOMs with minimal performance impact. Additionally, NC cavities can withstand power losses of several hundred watts with minimal performance impact, enabling the absorber to be positioned closer to the cavity for high absorption efficiency [14, 22].

The beam-line absorber, designed with a 380 mm diameter, damps HOMs, while a 200 mm transition section attenuates the accelerating mode, as illustrated in Fig. 12 [Figure 12: see original paper]. The absorbing material used here is ferrite-C48 with a thickness of 4 mm [29]. The cavity iris, with a 140 mm aperture diameter, facilitates HOM field propagation and accelerating mode rejection. Additionally, to reduce the loss factor, a taper measuring 100 mm in length and 63 mm in diameter at the exit is employed. The impedance spectrum of HOMs in the cavity was calculated using CST Microwave Studio and Particle Studio [23]. Eigenmode simulations were conducted to verify the peak impedance values of the critical modes. With the beam-line ferrite damper, the HOM impedance spectrum is illustrated in Fig. 13 Figure 13: see original paper and Fig. 13(b). The results indicate that longitudinal HOM impedances are below 4.0 $\mathrm{k\Omega \cdot GHz}$, and transverse HOM impedances are below 50 $\mathrm{k\Omega/m}$. The absorber reduces the impedance of the fundamental and harmonic modes by 0.1% and 2%, respectively, which are levels deemed acceptable.

Fig. 12. (Color online) The bimodal cavity with a beam-line HOM absorber.

Fig. 13. (Color online) (a) Longitudinal HOM impedance spectrum with the absorber. (b) Transverse HOM impedance spectrum with the absorber.

F. Thermomechanical Simulation and Design

The mechanical design focus was on the fundamental frequency tuning mechanism and the thermomechanical characteristics of the main structure. Fundamental frequency tuning is achieved by squeezing the cavity's end plate using a mechanical tuner. To achieve a frequency tuning range of 166.6 ± 0.25 MHz, a deformation of 1 mm is required at the cavity end plate. To minimize the deformation force, an arc groove was designed with a minimum wall thickness of 5 mm, as shown in Fig. 8(a). Simulation results indicate that a maximum deformation of 1 mm can be achieved by applying a pressure of 7.2 kN or a tension of 8.5 kN, as illustrated in Fig. 14 Figure 14: see original paper. The maximum mechanical stress at the end plate, when accounting for thermal stress contributions, reaches up to 68.6 MPa, as shown in Fig. 14(b). To maintain tuning within the elastic limit, the end plate must be made from forged copper, which possesses a yield strength exceeding 100 MPa. Additionally, to retain the properties of the forged copper, electron beam welding with minimal thermal impact should be employed for affixing the end plate to the cavity body [17].

Fig. 14. (Color online) (a) Cavity deformation under a tuning tension of 8.5 kN. (b) Stress distribution across the cavity resulting from the combined effects

of thermal expansion and the application of maximum tuning force. (c) Thermal temperature distribution across the cavity with a dissipated power of 40 kW.

The cooling system is designed to accommodate a maximum cavity power of 40 kW, corresponding to operating voltages of 320 kV for the fundamental mode and 200 kV for the harmonic mode. Based on the average power loss density across the inner cavity surfaces, the design includes 12 cooling pipes for the cavity mantle and 2 spiral-shaped cooling pipes for the inner conductor. Thermal analysis simulation results indicate that the maximum cavity temperature remains below 50°C, as depicted in Fig. 14(c). The temperature distribution results in a maximum thermal stress of 44 MPa at the inner conductor. The thermal deformation is 0.12 mm, leading to frequency changes of 68 kHz for the fundamental mode and 128 kHz for the third harmonic mode. Considering the adjustment ranges of 166.6\$±\$0.25 MHz for the fundamental mode and 499.8 ± 0.5 MHz for the third harmonic mode, the thermal deformation and frequency changes are within acceptable limits.

Heat generation in HOM absorbers arises from RF leakage heating and the HOM power induced by the beam. At the design operational levels of 320 kV for the fundamental mode and 200 kV for the harmonic mode, RF leakage heating from the two modes is less than 400 W. With a natural bunch length of 5.0 mm, the loss factor of the HOMs in the cavity is approximately 1.8 V/pC. The HOM power induced by the beam does not exceed 3 kW at a beam current of 500 mA. To ensure redundancy, the maximum heat load for the absorber was set at 5 kW in the design. Simulation results indicate that the maximum temperature of the ferrite remains below 55°C, with the temperature increase from inlet to outlet water not exceeding 8°C, as illustrated in Figs. 15 Figure 15: see original paper and 15(b).

Fig. 15. (Color online) (a) Temperature distribution of the ferrite absorber. (b) Temperature distribution in the HOM absorber and cooling system.

Comprehensive theoretical analysis and detailed simulations have established the feasibility of the bimodal cavity scheme. The tuning systems and input couplers, designed for the two operating modes, employ common techniques that facilitate ease of implementation. To achieve deep suppression of HOMs, a beamline absorber scheme was adopted for the coaxial RF cavity. This approach efficiently damps HOMs while maintaining a high shunt impedance [14, 21], although it requires sacrificing some longitudinal space. Where the requirement for HOM damping is less stringent, antenna-type HOM absorbers can be used [30], resulting in a more compact structure. Consequently, this bimodal cavity is also well-suited for space-constrained applications, such as compact light sources, medical accelerators, and industrial systems, where space efficiency and performance are critical.

Based on the presented design, the fabrication of the bimodal cavity with resonant frequencies of 166.6MHz and 499.8MHz has commenced.

SUMMARY

In this paper, a novel coaxial bimodal cavity, comprising both fundamental and third harmonic modes, has been proposed for advanced synchrotron light sources. This work addresses the longstanding challenges of achieving independent frequency tuning and effective HOM damping, thereby meeting the stringent requirements of advanced synchrotron radiation light sources. Compared to traditional separate fundamental and harmonic cavities, such bimodal cavities offer significant advantages in space efficiency and economic benefits.

This paper elucidates the principles of the coaxial bimodal cavity and presents a detailed prototype design with resonant frequencies of 166.6 MHz and 499.8 MHz for the defined application. Simulation results indicate that the cavity successfully achieved two accelerating modes for the fundamental and third harmonic systems, enabling independent frequency tuning, separate RF drives, and effective HOM damping. This research provides a compact and efficient solution for implementing double-frequency RF systems in advanced synchrotron light sources.

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Note: Figure translations are in progress. See original paper for figures.