

Novel rf design of bimodal normal-conducting active rf cavity for synchrotron radiation light sources

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Double-rf systems have become a standard solution in advanced storage ring light sources for beam acceleration and bunch lengthening. In this context, a compact single-cell normal-conducting bimodal rf cavity is proposed, in which the TM_{010} accelerating mode and the TM_{020} harmonic mode operate simultaneously within a single cavity. To suppress harmonic power leakage through the fundamental-mode coupler, a low-pass filter is introduced. In addition, tunable band-stop filters are employed to provide selective isolation of the operating modes and to enable efficient extraction and damping of parasitic higher-order modes. Based on this concept, a complete rf design of a single-cell bimodal cavity with a fundamental frequency of 500 MHz and a corresponding third-harmonic frequency of 1.5 GHz is presented, and key issues including frequency tuning, shunt impedance optimization, and higher-order-mode damping are systematically investigated. The results show that, under the condition of frequency matching between the two operating modes, their frequencies and coupling strengths can be adjusted with a high degree of independence. With higher-order modes effectively suppressed, the shunt impedances of the TM_{010} and TM_{020} modes reach 4.74 and 1.2 M Ω , respectively, corresponding to reductions of only 0.35% and 1.25% compared with the undamped case. These results validate a general design approach toward compact bimodal cavities for storage-ring double-rf systems. The mechanical design has been completed, and fabrication is currently in progress.

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I. INTRODUCTION

Storage ring light sources are widely used as versatile tools for fundamental research in the physical and life sciences [1]. Fourth-generation synchrotron light sources based on multibend achromat lattices are being developed worldwide, enabling diffraction-limited performance with ultralow beam emittance [2–6]. In such diffraction-limited storage rings (DLSRs), reduced beam energy and high single-bunch charge exacerbate coupled-bunch instabilities and intrabeam scattering, posing significant challenges to beam stability and lifetime [7,8]. Therefore, these facilities generally employ rf cavities with strong higher-order-mode (HOM) damping and incorporate higher-harmonic cavities

(HHCs) for bunch lengthening, thereby improving beam lifetime [9–15].

The double-rf system of storage ring comprises a fundamental rf system for beam acceleration and energy compensation, and a higher-order harmonic rf system for beam lengthening. The implementation of smaller vacuum apertures and lower emittance in DLSRs presents stringent requirements for the rf system [16]. In particular, the reduced tolerance to beam-driven instabilities necessitates stronger damping of cavity HOM impedances. These drivers have motivated the development of various improved and novel HOM-damped cavity designs [17–22].

The longitudinal manipulation of bunches using a fundamental rf cavity in conjunction with HHC is a validated scheme for significantly enhancing beam lifetime without compromising beam brightness [23,24]. HHC used for bunch lengthening does not provide energy to the bunch and typically designed as passive cavity [25]. Its electromagnetic field energy is induced by the beam, requiring no rf power source or coupler [26]. Additionally, actively driven HHC offer flexible operation and can be readily

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adapted to low beam-current conditions [27–29]. The principles and performance metrics of the rf cavity and HHC are nearly identical, and design paths are largely similar. By adjusting the voltage and phase experienced by electrons in the two frequency fields, the size of the potential well can be modified to achieve bunch lengthening or compression.

The bimodal (or dual-mode) structure concept represents a promising design strategy for rf structures. Its motivation is to enable a single cavity to support multiple functions by integrating designs that are otherwise realized in separate rf structures [30,31]. By superposing multiple fields in a single cell, the geometry can be more compact. Some bimodal rf structures have been investigated in several accelerator research programs [32–35]. For example, Wang *et al.* designed a bimodal rf gun aiming to generate electron beams with reduced emittance and energy spread [36]. Rajabi *et al.* designed a dual-mode injector cavity intended for chopping and compressing a dc electron beam [37]. More recently, in a different application, Gong *et al.* developed a variable polarization dual-mode transverse deflecting structure, enabling arbitrary control of the beam deflection direction through the superposition of fields with different deflecting orientations [38,39]. A common feature among these designs is the use of two modes to manipulate the electron beam, thereby enabling improved beam performance or expanded functionality. The primary challenge is to control the frequencies and field profiles of the different modes under both intrinsic geometric design constraints and specific operational requirements.

In this work, we first investigate the operating conditions of a double-rf system for bunch length manipulation. We then propose a novel bimodal HOM-damped rf cavity scheme employing two power couplers, isolators to suppress harmonic power leakage, and band-stop waveguides for controlled HOM extraction, and discuss their effects on the rf performance of the cavity. The cavity geometry is optimized using a multiobjective optimization algorithm, and the resulting rf and thermal performances are presented.

Motivated by the integration of the fundamental and third-harmonic functions in rf applications for advanced light source, particularly compact storage-ring-based EUV light sources under study [40], we design a compact and multifunctional bimodal cavity that integrates the TM₀₁₀ fundamental mode at 500 MHz and the TM₀₂₀ third-harmonic mode at 1500 MHz within a single structure. The main parameters of the reference device are summarized in Table I.

The structure of this paper is organized as follows. Section II analyzes the operating conditions of a double-rf system for bunch lengthening and compression and introduces the proposed bimodal cavity scheme. Section III presents the detailed cavity design, including the bimodal rf design, HOM extraction, and damping structures, as well as the mechanical design and thermal analysis. Finally,

TABLE I. Main parameters of the storage ring for a fully coherent lightsource.

Parameter	Value	Unit
Beam energy	1.40	GeV
Circumference	172.8	m
Momentum compaction factor	7.67×10^{-4}	
Relative energy spread	8.0×10^{-4}	
Bunch charge	2.88	nC
Reference bunch length	2.89	mm
Energy loss per turn	1.1	MeV
Fundamental rf frequency	499.7	MHz
rf voltage (per cavity)	500	kV
Harmonic rf frequency	1499.1	MHz

Sec. IV concludes the paper and discusses prospects for future work.

II. THEORY AND SCHEME OF THE BIMODAL RF CAVITY

A. The double-rf system

The new generation synchrotron light sources based on electron storage rings typically employ a double-rf system to enhance beam lifetime. The voltages seen by electrons in the main rf cavity and the n th harmonic cavity can be expressed as [41]:

$$V(\phi) = V_{\text{rf}} \sin(\phi + \phi_s) + V_n \sin(n\phi + n\phi_{\text{ns}}), \quad (1)$$

where V_{rf} and V_n are the peak voltages of the fundamental and harmonic cavity and ϕ_s and ϕ_{ns} denote their synchronous phases. The synchrotron-radiation energy loss per turn of per bunch U_0 is compensated by the combined action of both rf systems, satisfying the relation:

$$eV(0) = eV_{\text{rf}} \sin(\phi_{\text{rf}}) + eV_n \sin(\phi_n) = U_0, \quad (2)$$

where U_0 is the synchrotron-radiation energy loss. Bunch lengthening is obtained by flattening the rf potential around the bunch center. A commonly used operating condition for maximum lengthening is to impose vanishing first- and second-order slopes at the bunch center [42,43]. The voltage and phase of the rf cavity and the harmonic cavity satisfy the following relation:

$$\begin{aligned} V_n &= \sqrt{\frac{V_{\text{rf}}^2(n^2 - 1) - n^2 U_0^2}{n^2(n^2 - 1)}}, \\ \phi_s &= \arcsin\left(\frac{n^2 U_0}{V_{\text{rf}}(n^2 - 1)}\right), \\ \phi_{\text{ns}} &= \frac{1}{n} \arcsin\left(-\frac{U_0}{V_n(n^2 - 1)}\right). \end{aligned} \quad (3)$$

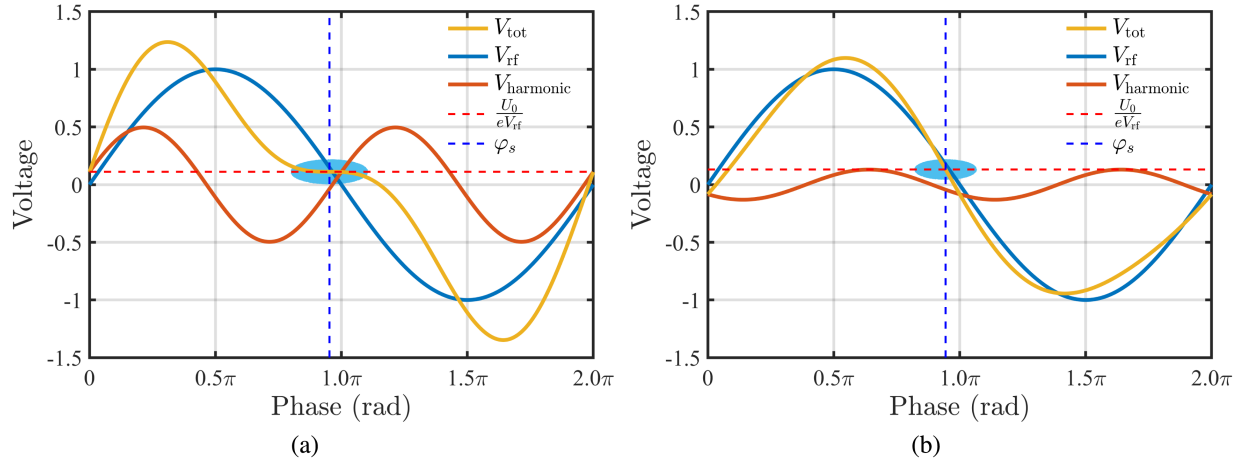


FIG. 1. Voltage (normalized by V_{rf}) and phase relationships required for (a) bunch lengthening and (b) bunch shortening.

Together with Eq. (2), these conditions determine the required voltage ratio V_n/V_{rf} and phases (ϕ_s, ϕ_{ns}) for a given harmonic number n and V_{rf} . Typically, the phase ϕ_s is defined within the range $(\pi/2, \pi)$, corresponding to ϕ_{ns} in the interval $(-\pi/2, 0)$. As shown in Fig. 1(a), the bunch passes through the cavity when it is located at the flattest position of the rf potential well.

Bunch compression can similarly be achieved by adjusting the cavity voltages and phases in the double-rf system, as illustrated in Fig. 1(b). In conventional implementations, the fundamental and harmonic systems are realized by separate cavities and rf chains, which naturally avoids crosstalk between the two operating frequencies. In the proposed bimodal cavity, both modes coexist within a single cell, making port-to-port isolation and independent tuning essential design requirements.

For electron storage rings where $U_0 \ll eV_{rf}$, the optimum voltage ratio for lengthening is of order $V_n/V_{rf} \sim 1/n$ implying that a third-harmonic system can achieve the desired potential flattening with a lower harmonic voltage than a second-harmonic scheme. This motivates the choice of a third-harmonic operating mode in this work.

B. Scheme of the bimodal cavity

Based on the operational principles of double-rf systems, a novel bimodal cavity scheme is proposed, as illustrated in Fig. 2. This design incorporates two resonant modes, TM_{010} and TM_{020} , within a single cavity structure. Owing to their distinct geometric sensitivities, the resonant frequencies of these modes can be tailored to form a harmonic relationship. Specifically, the resonant frequency of the TM_{020} mode can be designed to be 3 times that of the TM_{010} mode. This configuration effectively replicates the conventional arrangement of a fundamental rf cavity combined with a third-harmonic cavity, while enabling substantial spatial integration.

In this scheme, both operating modes are driven actively. To realize this configuration, a fundamental power coupler

(FPC) and a third-harmonic power coupler (THPC) are employed for the TM_{010} and TM_{020} modes, respectively. One consideration for adopting the active scheme in this work is that it provides controllable harmonic voltage and helps overcome the limitation of passive harmonic cavities under low-current operation, where stable operation and beam tuning are generally less convenient.

To prevent power leakage of the higher-frequency TM_{020} mode through the fundamental coupler port, a low-pass filter is introduced in the proposed scheme to improve the isolation between the TM_{020} mode and the TM_{010} power coupler. In addition, to suppress undesired energy transfer

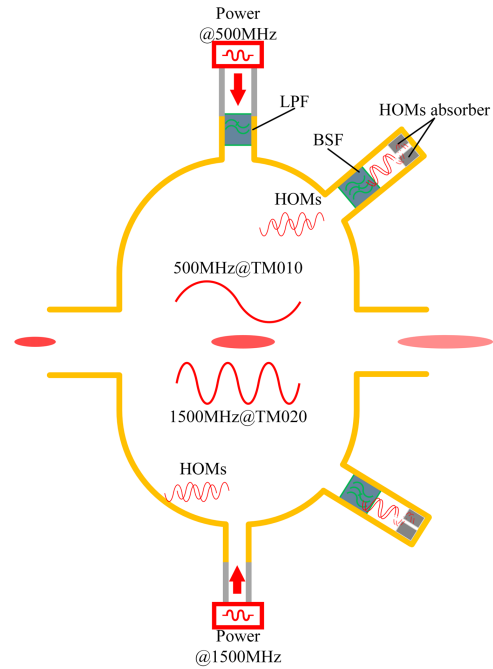


FIG. 2. Scheme of the bimodal rf cavity. LPF denotes the low-pass filter, BSF denotes the band-stop filter, and three waveguide dampers adopted in this work.

and damping of the TM_{020} mode through the HOM damper coupler, a band-stop filter is also introduced for this purpose.

III. DESIGN OF THE BIMODAL RF CAVITY

For a bimodal rf cavity, since the frequencies of the TM_{010} and TM_{020} modes are not harmonically related, the cavity geometry needs to be carefully tailored to satisfy the frequency requirements of both modes simultaneously. Under this constraint, the rf design aims to optimize the performance of two operating modes. The detailed design considerations and optimization procedures are presented in the following subsections.

A. Bimodal rf design

To achieve frequency matching between the modes, the cavity's geometric structure is parameterized, structure of the cavity can be freely adjusted these parameters. A planar schematic of the cavity's outer contour as shown in Fig. 3. The resonant frequencies of the cavity are calculated using the eigenmode solver in CST Studio Suite [44]. Through a systematic parametric study of the cavity geometry, four geometric parameters are identified as having a dominant influence on the resonant frequencies of the TM_{010} and TM_{020} modes. Moreover, these parameters exhibit different frequency sensitivities for the two modes, as illustrated in Fig. 4.

For clarity in comparing the frequency tuning trends in Fig. 4, the frequency of the TM_{010} mode is shifted upward by 1000 MHz in the plot. The quality factor and R/Q of both modes exhibit an approximately linear dependence on the selected geometric parameters within the scanned ranges. In particular, the cavity radius r shows a strong influence on the resonant frequencies, with tuning slopes of $k_{TM_{010}} = -2.31$ MHz/mm and $k_{TM_{020}} = -10.76$ MHz/mm. By contrast, the nose-cone gap g yields turning slopes of $k_{TM_{010}} = 2.31$ MHz/mm and $k_{TM_{020}} = 0.29$ MHz/mm.

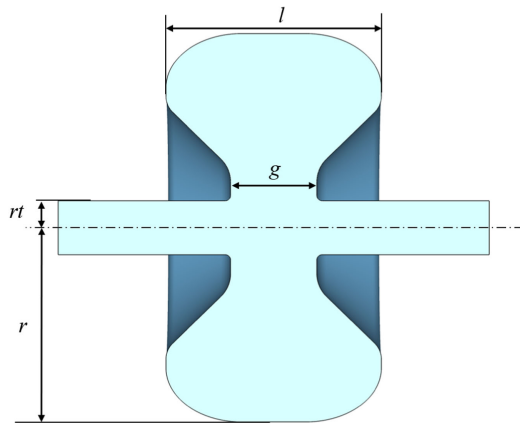


FIG. 3. Cross-sectional view of the main cavity.

In the present design, the resonant frequency of the TM_{020} mode lies between 2 and 3 times that of the TM_{010} . Consequently, increasing the TM_{020} mode frequency is necessary and can be efficiently achieved by reducing the cavity radius r , while a simultaneous reduction of the nose-cone gap g allows the TM_{010} mode frequency to be maintained within the required range. As shown in Fig. 4(b), variation of the cavity length l provides additional flexibility for fine frequency adjustment, and the combined tuning ranges of the other three parameters are sufficient to achieve frequency matching of the two modes.

Although the beam-pipe radius rt exhibits a pronounced effect on tuning the TM_{020} mode frequency, as illustrated in Fig. 4(d), it also leads to a significant reduction in R/Q and offers a relatively limited tuning range. Therefore, rt is not selected as a primary design parameter for frequency matching. In addition, several rounded fillets are introduced at critical locations to reduce the peak surface electric field, and elliptical fillets with different major-to-minor axis ratios are employed. The nose-cone height and the angle between the nose cone and the cavity sidewalls are also parameterized, providing sufficient design freedom for subsequent multiobjective optimization while preserving the frequency-matching conditions.

In this work, a multiobjective optimization is performed for the parameter design of the bare bimodal cavity. At this stage, the bare-cavity model offers a relatively large number of geometric degrees of freedom, and the relationships between the design parameters and the bimodal operating frequencies as well as the rf performance metrics are comparatively smooth, making it suitable for establishing a baseline cavity design. After the integration of additional functional structures in the complete cavity model, the rf performance is further refined through parametric adjustments.

During the optimization, matching of the bimodal operating frequencies is assigned the highest priority. Under this constraint, eight key geometric parameters are selected as design variables, and the shunt impedance and quality factor of the TM_{010} and TM_{020} modes are optimized in a multiobjective framework. The optimization workflow is implemented through a coupled MATLAB–CST environment, as illustrated in Fig. 5.

The multiobjective optimization results reveal clear trade-offs between the shunt impedance and quality factor of the two operating modes, with the optimization directed toward simultaneously improving the rf performance of the TM_{010} and TM_{020} modes. As shown in Fig. 5(a), the Pareto front of the shunt impedance, highlighted by the red points, delineates the achievable performance boundary for the two modes. Given that the operating voltage required for the third-harmonic mode is significantly lower than that of the fundamental accelerating mode, the solution selection prioritizes a higher shunt impedance for the TM_{010} mode to satisfy the primary acceleration requirement.

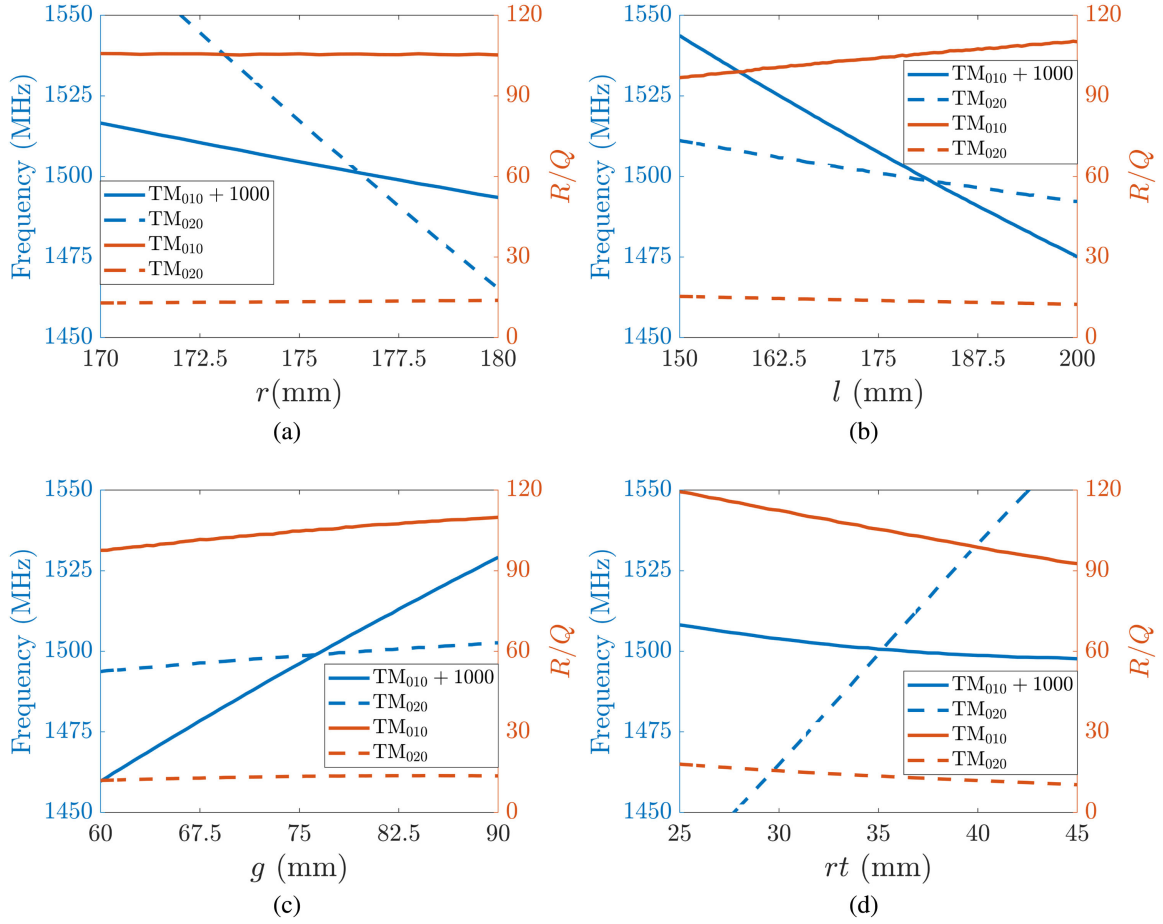


FIG. 4. Dependence of the frequencies and R/Q of the TM_{010} and TM_{020} modes on the cavity geometric parameters. The left vertical axis corresponds to the resonant frequency (blue curves), while the right vertical axis corresponds to R/Q (orange curves). Solid lines represent the TM_{010} mode, and dashed lines represent the TM_{020} mode: (a) cavity radius, (b) cavity length, (c) gap length, and (d) beam-pipe radius.

The distribution of the quality factors for the two modes is presented in Fig. 5(b), exhibiting trends consistent with the shunt impedance optimization. In the selection of the quality factors, the TM_{010} mode is likewise given priority, thereby maximizing the overall rf efficiency of the

fundamental mode while maintaining acceptable performance for the third-harmonic mode.

During the optimization, the operating frequencies of both modes are constrained within a predefined narrow range to ensure frequency matching. The results indicate

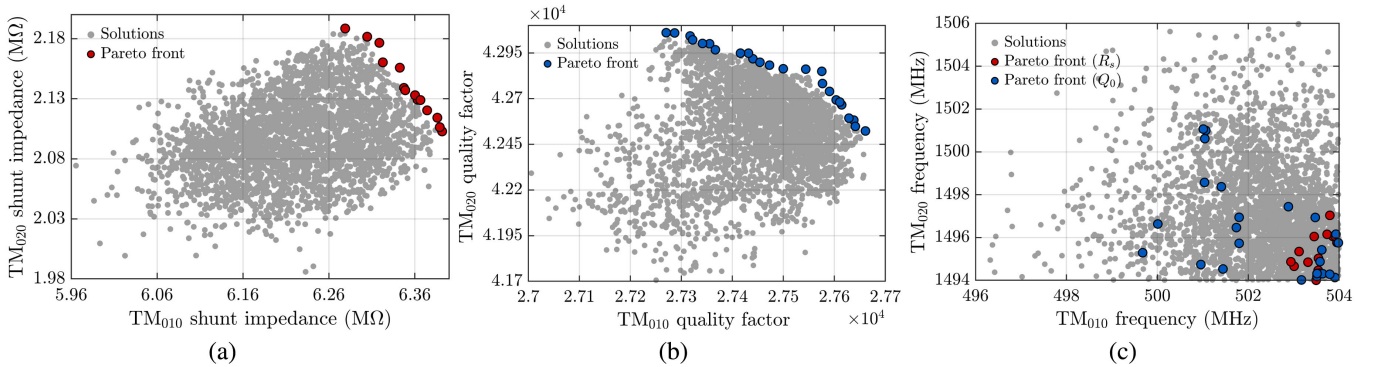


FIG. 5. (a) Optimization workflow and Pareto front for the shunt impedances of the TM_{010} and TM_{020} modes. (b) Optimization workflow and Pareto front for the quality factors of the TM_{010} and TM_{020} modes. (c) Frequency evolution in the two optimization processes and the corresponding frequency points of the Pareto-front solutions.

that performance extrema are typically associated with solutions featuring a slightly higher fundamental-mode frequency and a slightly lower harmonic-mode frequency, as shown in Fig. 5(c).

The resulting frequency deviations are small and can be compensated in subsequent design stages through minor adjustments of geometric parameters not included in the optimization. Consequently, the obtained solutions serve as a reasonable baseline for the bare-cavity design, providing a starting point for further refinement of the complete cavity configuration.

B. Tuner and coupler

In the proposed bimodal cavity scheme, two piston-type tuners are implemented to provide sufficient frequency tuning flexibility for the two operating modes. This is required because the mechanical displacement of a tuner simultaneously perturbs the resonant frequencies of both the TM_{010} and TM_{020} modes, and a single tuner does not offer enough degrees of freedom to control the two frequencies independently. Figure 6 shows the locations of the two tuners in the cavity, with radial positions of 40 and 20 mm, respectively.

Figure 7 illustrates the frequency shifts of the fundamental and third-harmonic modes as functions of the tuner insertion depth. For tuner 1, the frequency variations of both modes exhibit a clear linear dependence on the insertion depth, with tuning sensitivities of

$k_{11} = 0.08$ MHz/mm for the TM_{010} mode and $k_{12} = 0.0265$ MHz/mm for the TM_{020} mode. In comparison, tuner-2 also shows an approximately linear tuning behavior within its effective stroke range of 20–40 mm, yielding tuning slopes of $k_{21} = 0.02$ MHz/mm and $k_{22} = -0.244$ MHz/mm for the TM_{010} and TM_{020} modes, respectively. The frequency shifts induced by the two tuners can be written in a linear form as

$$\begin{pmatrix} \Delta f_1 \\ \Delta f_2 \end{pmatrix} = \begin{pmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{pmatrix} \begin{pmatrix} l_1 \\ l_2 \end{pmatrix}, \quad (4)$$

where k_{mn} denotes the frequency sensitivity of tuner n on mode m , l_1 and l_2 denote the displacements of tuner 1 and tuner 2, respectively, and $\Delta f_{1,2}$ represent the frequency shifts of TM_{010} and TM_{020} . The tuning matrix is non-singular, allowing independent control of the two modal frequencies through coordinated tuner motion. The tuning range is given by

$$\begin{aligned} |\Delta f_2|_{\max} &= |\det(\mathbf{K})| \min \left(\frac{L_1}{|k_{12}|}, \frac{L_2}{|k_{11}|} \right), \\ |\Delta f_1|_{\max} &= |\det(\mathbf{K})| \min \left(\frac{L_1}{|k_{22}|}, \frac{L_2}{|k_{21}|} \right), \end{aligned} \quad (5)$$

where $\mathbf{K} = \{k_{mn}\}$ is the tuning sensitivity matrix, and L_n is the available mechanical stroke of tuner n . With tuner 1 operating over 0–20 mm and tuner 2 over 20–40 mm, the achievable independent tuning ranges are limited by the dominant displacement required in each independent tuning direction, leading to

$$\begin{aligned} \Delta f_1 &\approx 3.29 \text{ MHz}, \\ \Delta f_2 &\approx 10.03 \text{ MHz}. \end{aligned} \quad (6)$$

Considering realistic fabrication tolerances, the required tuning range of the TM_{010} mode is typically on the order of 1 MHz, whereas a larger tuning range is generally needed for the TM_{020} mode, since it is more sensitive to structural variations caused by fabrication errors and temperature changes. With the present tuner dimensions of $r_{TM_{010}} = 40$ mm and $r_{TM_{020}} = 20$ mm, the available frequency margin is expected to be adequate for practical application. In general, however, the tuner stroke only needs to satisfy the operational requirement, since excessive tuner penetration may introduce field distortion and additional thermal loading.

In operation, by taking advantage of the linear tuning regime, the cavity frequency can be adjusted within one or two iteration steps, providing tuning speed and sensitivity comparable to those of a single-tuner scheme. The mechanical tuners are first used for coarse tuning to bring the cavity frequency close to the target operating point, after which the final frequency correction and locking are

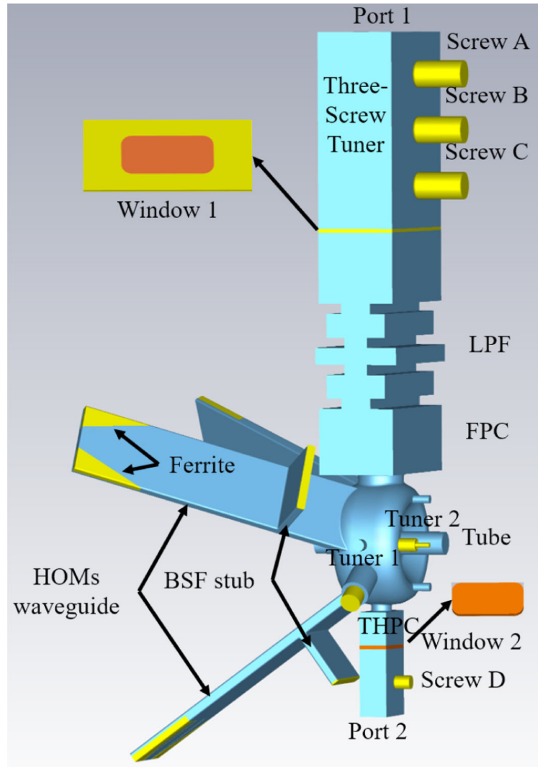


FIG. 6. Full 3D model of the bimodal cavity.

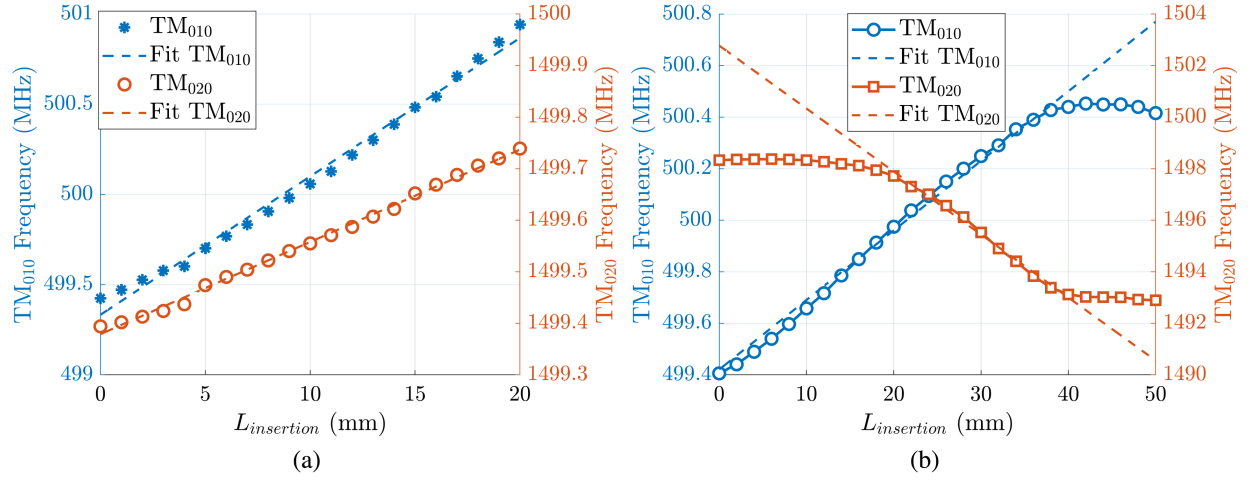


FIG. 7. Variation of bimodal cavity frequency with (a) tuner 1 and (b) tuner 2 insertion length.

achieved by the LLRF system using standard feedback algorithms, such as PID or adaptive control [45].

Two coupling apertures of different sizes are introduced on the cavity equatorial plane to provide active rf power feeding at both operating frequencies. These apertures are connected to standard WR-1800 and WR-650 rectangular waveguides for the fundamental and third-harmonic modes, respectively. At the fundamental-mode coupling port, a waveguide-based low-pass filter is incorporated to provide frequency selectivity. The filter exhibits a sufficiently wide passband to transmit the fundamental rf power while effectively suppressing power leakage at the third-harmonic frequency.

The transmission coefficients of the two operating modes illustrate the isolation performance of the adopted coupling scheme, as shown in Fig. 8. Owing to the weak coupling of the third-harmonic coupling aperture, effective isolation

with respect to the fundamental mode is achieved, with an isolation level of $S_{12} < -36.5$ dB at the fundamental frequency of 499.4 MHz. After introducing the band-stop filtering section in the fundamental-mode coupling path, the third-harmonic signal is effectively isolated as well, yielding $S_{21} < -38$ dB at the third-harmonic frequency of 1498.42 MHz. As a result, sufficient mutual isolation between the two operating modes is obtained.

To provide vacuum sealing, two planar ceramic windows made of low-loss alumina are incorporated into the bimodal cavity. One is located between the LPF port and the three-stub waveguide tuner, while the other is installed at the THPC port. Both windows are placed at positions of minimum reflected power in order to minimize their influence on the coupling characteristics.

A three-stub waveguide tuner is installed at one end of the bandpass filtering section connected to the FPC port,

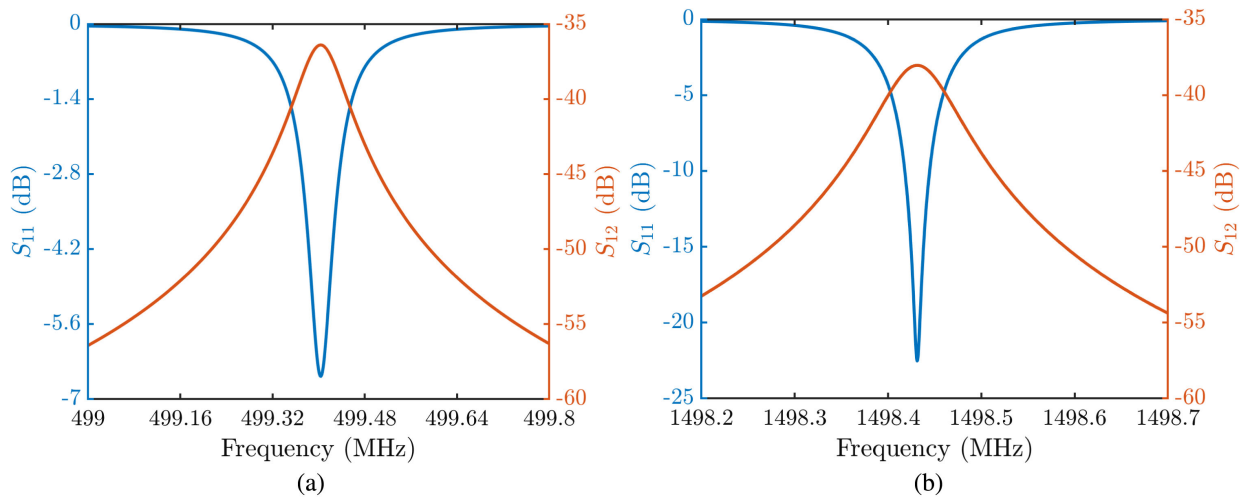


FIG. 8. Simulated S -parameters of the two rf couplers in the bimodal cavity. (a) Fundamental-mode input coupler (port 1, $\beta = 2.8$), illustrating the isolation from the third-harmonic port. (b) Third-harmonic coupler (port 2, $\beta = 1.15$), showing the corresponding isolation from the fundamental-mode port.

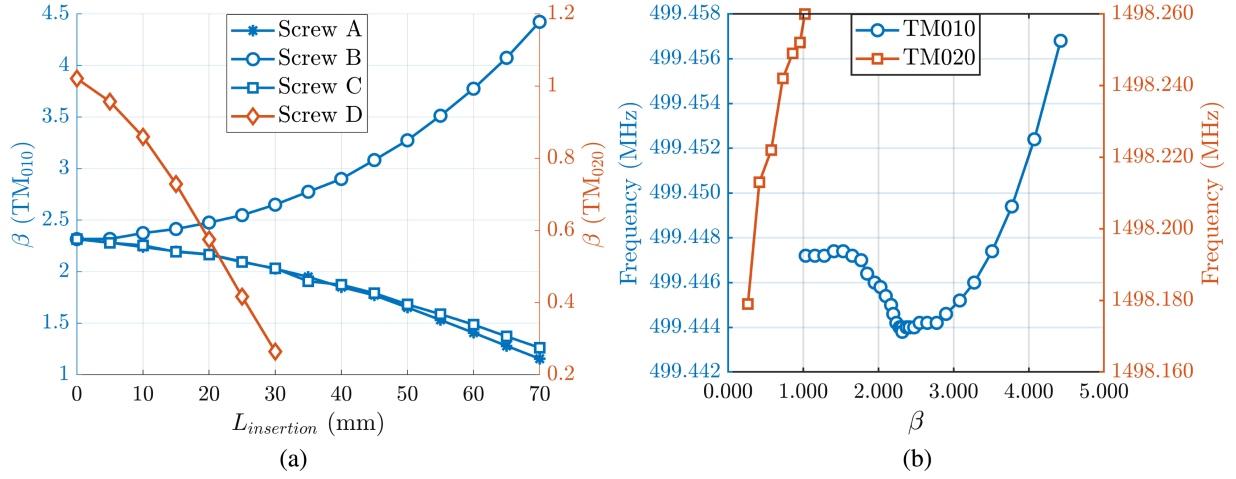


FIG. 9. (a) Dependence of the coupling coefficient on the tuner stroke for the three-stub coupler in the TM_{010} mode (left axis) and the single-stub coupler in the TM_{020} mode (right axis). (b) Relationship between the coupling coefficient and the resonant frequency of the two operating modes, with the left axis corresponding to TM_{010} and the right axis to TM_{020} .

enabling tunability of the external coupling for the fundamental mode. For the fundamental-mode coupler, an adjustable external coupling factor in the range of 1.2–4.5 is achieved, while the third-harmonic coupler provides a tunable coupling factor from 0.2 to 1.0 through a single-stub tuning structure, as shown in Fig. 9(a). Figure 9(b) further shows the corresponding frequency shifts of the operating modes induced by the coupling adjustment, which are about 13 and 80 kHz, respectively.

C. HOMs extraction and damper

Employing the TM_{020} mode as the third-harmonic operating mode for bunch manipulation imposes physical constraints on HOM extraction and damping that differ from those of conventional cavities. In standard rf cavities operating solely in the TM_{010} mode, the fundamental frequency is typically lower than that of most parasitic modes. Under such a spectral configuration, high-pass coaxial or rectangular waveguide couplers can be used to extract HOM power in a relatively straightforward manner.

For cavities in which the operating mode is not the lowest-frequency mode, HOM damping becomes significantly more complex. In the TM_{020} accelerating cavity proposed by Ego *et al.* [19], the HOM coupling apertures are placed at locations where the TM_{020} magnetic field is weak, allowing the low-frequency TM_{010} mode to be damped while reducing the loading imposed on the operating mode.

In a bimodal cavity, the constraints are further tightened: parasitic modes detrimental to beam stability are distributed between the two operating modes TM_{010} and TM_{020} . Consequently, the HOM damping design of a bimodal cavity must selectively suppress these parasitic modes while controlling the coupling-induced loading on both operating modes.

Based on the above analysis, the HOM damping scheme adopted in this work employs rectangular hollow waveguides as the extraction structures for HOM, in combination with band-stop waveguides to isolate the third-harmonic power. The HOM couplers are located in the transition region between the cavity end wall and the equator, as illustrated in Fig. 6. Three coupling apertures are uniformly distributed along the cavity circumference with an angular separation of 120° and are oriented at a prescribed angle with respect to the cavity wall. By adjusting the dimensions of the coupling apertures and their positions on the cavity, the coupling strengths of different high-order modes can be effectively controlled.

For a waveguide band-stop structure based on a short-circuited shunt stub operating in the TE_{10} mode, the center isolation frequency f_0 is primarily determined by the stub length l and can be approximated as

$$\frac{2\pi f_0}{c} \sqrt{1 - \left(\frac{c}{2af_0}\right)^2} l \approx \frac{3\pi}{2}, \quad (7)$$

where a is the broad-wall dimension of the rectangular waveguide. As shown in Fig. 10(a), the adopted rectangular waveguide has a cross-sectional dimension of $210 \text{ mm} \times 30 \text{ mm}$, corresponding to a TE_{10} cutoff frequency of 0.714 GHz. This cutoff frequency is selected to lie between the fundamental-mode frequency and that of the first higher-order cavity mode TM_{110} . Under this condition, coupling apertures with the same cross-sectional dimensions place the targeted higher-order modes within the propagating band of the waveguide, enabling efficient extraction of HOM power.

The relationship between the center isolation frequency and the stub length of the band-stop structure is obtained using the frequency-domain solver, as shown in Fig. 10(b).

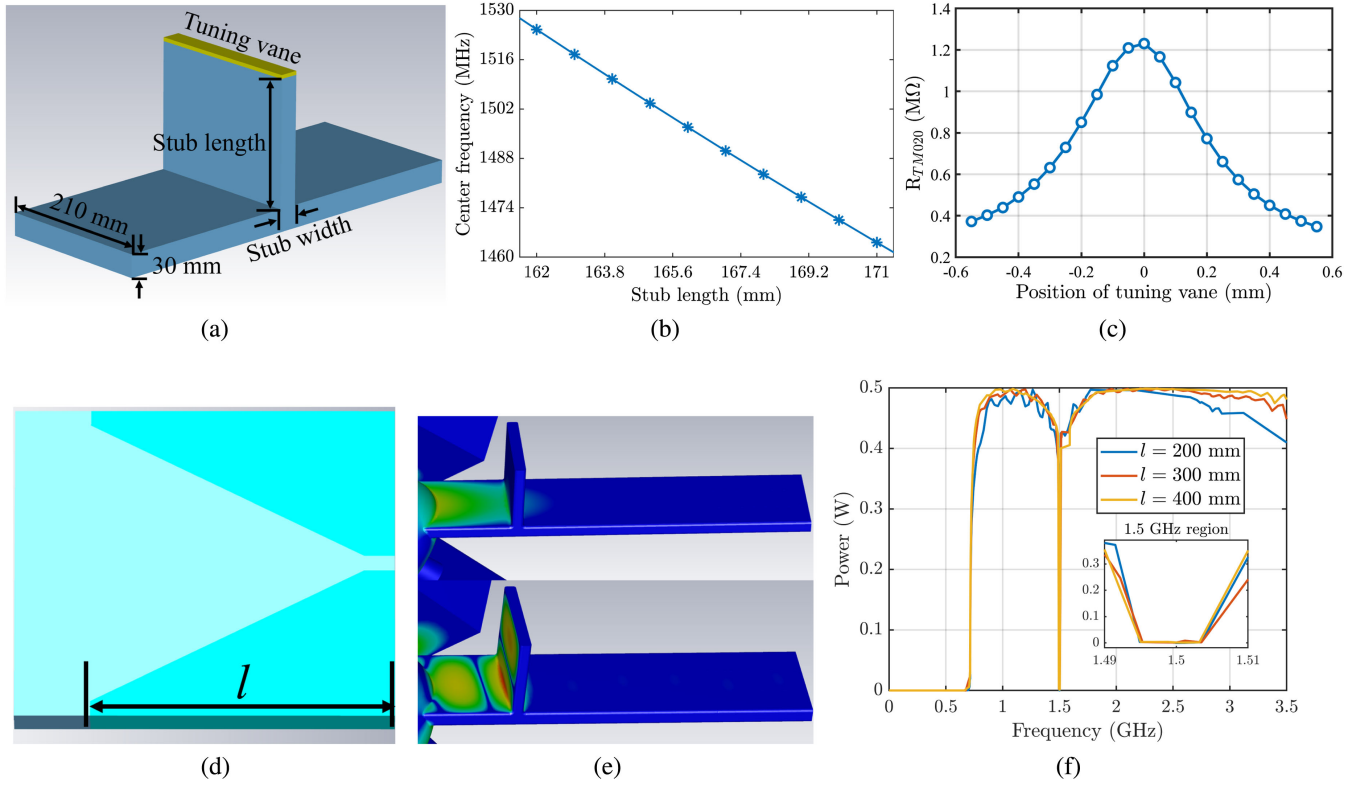


FIG. 10. (a) Schematic of the waveguide band-stop structure. (b) Dependence of the isolation center frequency on the stub length. (c) Dependence of the TM_{020} shunt impedance on the tuning-vane position for fine adjustment of the stub short-circuit position. (d) Model of the HOM damper. (e) Electric-field distributions in the HOM-damper waveguide (top: TM_{010} , bottom: TM_{020}). (f) Absorbed power curves of the HOM damper.

The results indicate that the transmission of the third-harmonic power can be precisely suppressed by adjusting the stub length.

By adjusting the position of the tuning vane located above the short-circuited stub, the center isolation frequency of the band-stop structure can be modified. This variation is also reflected in the performance of the full cavity. For the TM_{010} mode, the coupling coefficient to the band-stop branch is sufficiently small, such that the contribution of the branch impedance to the total cavity shunt impedance is negligible. In contrast, for the TM_{020} mode, the stronger coupling to the band-stop branch leads to a pronounced influence, manifested as observable changes in the shunt impedance of the TM_{020} mode with the tuning vane position.

As shown in Fig. 10(c), the shunt impedance of the TM_{020} mode in the full cavity exhibits a pronounced sensitivity to the tuning vane position. Here, the tuning vane position of zero corresponds to the initial reference configuration adopted in this study. The stub width has a pronounced influence on the isolation bandwidth, in the present design, a stub width of 20 mm is selected, resulting in a -20 dB isolation bandwidth of approximately 15 MHz and a -3 dB bandwidth of about 145 MHz. This parameter choice satisfies the requirement

of third-harmonic isolation while maintaining sufficient bandwidth for effective damping of nearby higher-order modes.

After being extracted through the waveguides, the high-order modes are dissipated in the absorbing materials terminated at the waveguide ends. In the simulations, the absorber is modeled using equivalent dielectric and magnetic dispersion characteristics fitted to measured ferrite data, as shown in Fig. 10(d), the electric-field distributions of the TM_{010} and TM_{020} modes in the waveguide damper are presented in Fig. 10(e). After coupling through the HOM coupler, the TM_{020} mode propagates in the rectangular waveguide in the TE_{10} mode. By connecting the BSF section to the absorber, a waveguide damper is formed, with a port terminated on the opposite side. The corresponding power-absorption curve of the damper is shown in Fig. 10(f). To reduce material reflection, the ferrite absorber adopts a wedge-shaped profile. Among the absorber parameters, the ferrite length has the most pronounced influence on the absorption performance, and improved absorption is obtained with increasing length. The stopband width is about 8 MHz, within which the absorbed power remains below 1%. Outside the stopband, the absorption rises rapidly, enabling effective damping of higher-order modes in the vicinity of 1.5 GHz.

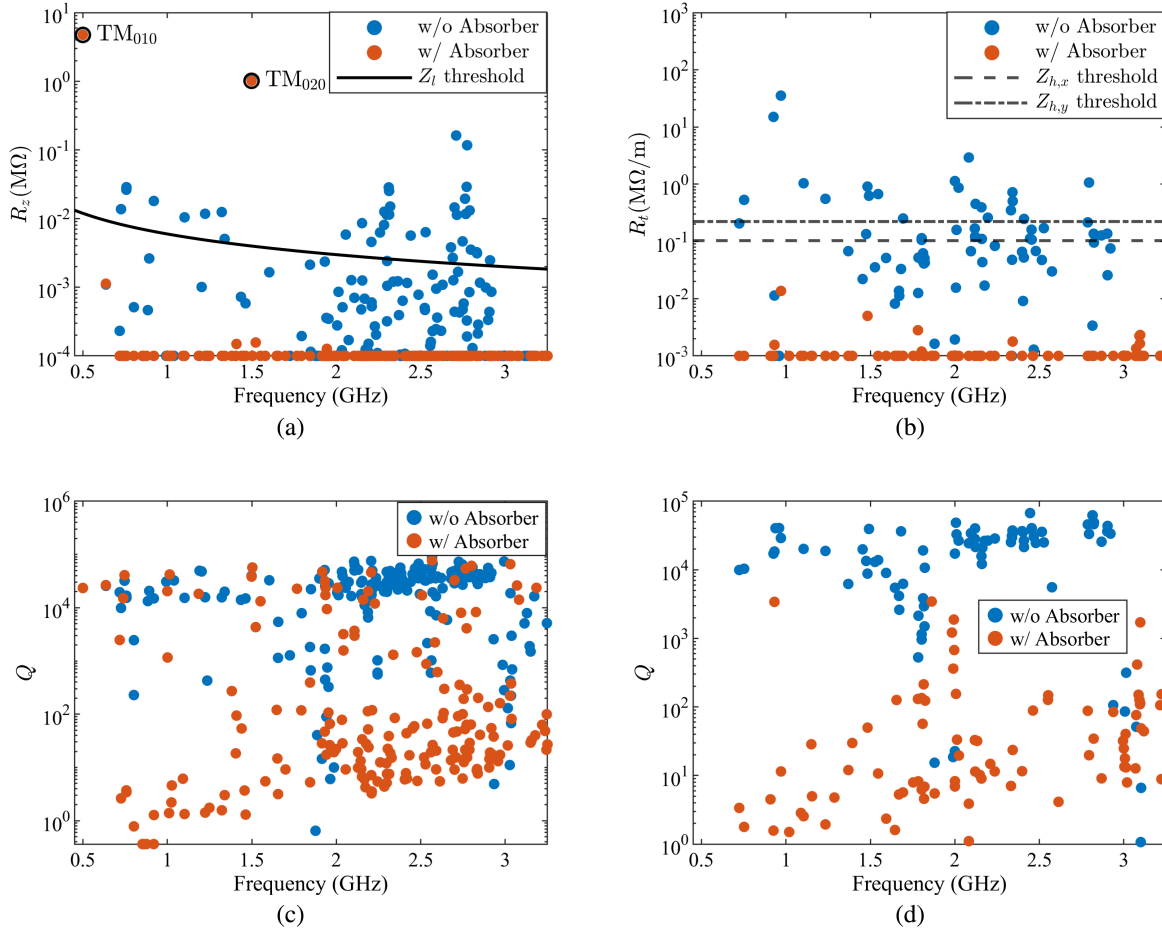


FIG. 11. Shunt impedance and quality-factor distributions of monopole and dipole modes with and without HOM absorbers. Blue symbols denote cases without absorbers, and red symbols denote cases with absorbers. (a) Monopole shunt impedances, with the accelerating TM_{010} mode marked by a circle and the harmonic TM_{020} mode marked by a square. (b) Dipole shunt impedances. (c) and (d) Corresponding quality factors of the monopole and dipole modes.

Figure 11 compares the shunt impedance and quality-factor distributions of the cavity with and without the HOM absorbers. Figure 11(a) shows that, after introducing the HOM damping structures, the shunt impedance of the TM_{010} mode is 4.74 MΩ (a decrease of less than 0.4%), while that of the TM_{020} mode is 1.2 MΩ (a decrease of approximately 1.25%). In contrast, the parasitic higher-order modes are significantly suppressed, as shown in Figs. 11(a) and 11(b), and the quality factors of the dipole modes are reduced more markedly than those of the monopole modes, as presented in Figs. 11(c) and 11(d). The longitudinal HOM impedances are reduced to the order of 1 kΩ, and the transverse HOM impedances are reduced to about 13 kΩ/m. These results demonstrate that the proposed damping scheme effectively suppresses HOMs while introducing only minor degradation to the rf performance of the operating modes.

The rf characteristics of the TM_{010} and TM_{020} modes are summarized in Table II. It should be noted that the shunt impedances of the TM_{010} and TM_{020} modes obtained from

the full-cavity analysis are lower than those from the bare-cavity multiobjective optimization. This reduction primarily arises from the inclusion of functional components in the complete cavity model (e.g., power couplers, tuners, and HOM extraction waveguides), which modify the electromagnetic field distribution and the effective cavity parameters.

TABLE II. rf parameters of the TM_{010} and TM_{020} mode.

Parameters	TM_{010}	TM_{020}	Unit
Frequency	499.4	1498.2	MHz
Shunt impedance	4.74	1.2	MΩ
Unloaded Q_0	24,400	41,500	
R/Q	194.3	28.9	Ω
Tuning range ^a	3.29	10.03	MHz
Coupling coefficient β^b	1.2–4.5	0.2–1.0	

^aTuner strokes: Tuner 1: 0–20 mm, and tuner 2: 0–40 mm.

^b TM_{010} coupling is adjusted by three-screw tuners; TM_{020} coupler tuner stroke: 0–30 mm.

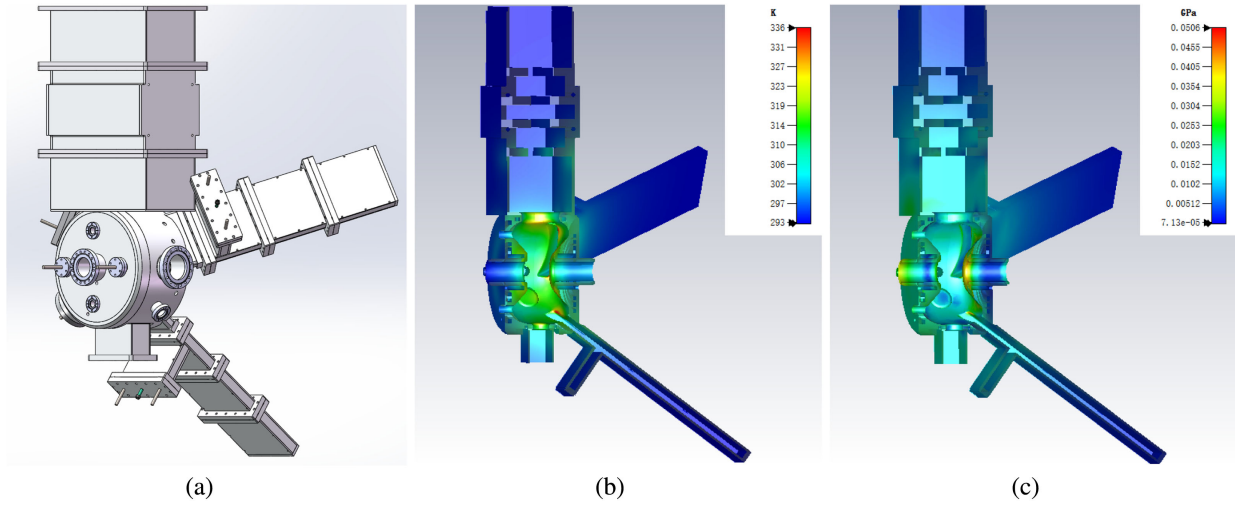


FIG. 12. (a) Mechanical model. (b) Temperature distribution across the cavity under rf power dissipation of 42.72 kW in the TM_{010} mode and 18.75 kW in the TM_{020} mode. (c) Stress distribution across the cavity resulting from the combined effects of thermal expansion.

D. Mechanical design and thermal analysis

After completing the rf optimization of the bimodal cavity, a detailed mechanical design study is carried out to enable the engineering integration of the rf design, addressing key issues related to the cavity geometry, tuning scheme, power coupling configuration, and high-order-mode isolation and damping. The optimized cavity has a radius of 183 mm and a length of 205 mm, resulting in a compact overall structure. The corresponding mechanical design is shown in Fig. 12(a).

To achieve effective isolation of the TM_{020} mode, the short-circuited stub in the band-stop isolator is implemented using a piston-type adjustable structure. This section is connected to the rectangular waveguides on both sides via flanges, forming a detachable and modular configuration. By replacing the band-stop section with a straight waveguide, effective damping of the TM_{020} mode can be realized. This design allows the cavity to retain its bimodal operating capability while enabling configuration changes to operate either as a single-mode accelerating cavity or in a passive third-harmonic mode, thereby enhancing the operational flexibility of the bimodal cavity under different running conditions.

In the proposed bimodal cavity, the shunt impedances of the TM_{010} and TM_{020} operating modes are 4.74 M Ω and 1.2 M Ω , respectively. Under typical operating conditions, as shown in Table I, a fundamental cavity voltage of 500.0 kV requires an rf power dissipation of approximately 52.74 kW. For the optimal bunch lengthening condition, the required cavity voltage of the third-harmonic mode is about 167.0 kV, corresponding to an rf power dissipation of approximately 23.24 kW. As a result, the total rf power dissipated in the bimodal cavity under simultaneous bimodal operation is approximately 75.98 kW.

To accommodate this power level and ensure thermal-mechanical stability under steady-state operation, an appropriate water-cooling scheme is implemented. Dense cooling channels are embedded in the cavity side walls, while enlarged cooling grooves are designed in regions with high rf power density, such as the nose cones. In addition, local cooling channels are incorporated around the power coupling apertures, the HOM extraction waveguides, and the short-circuited stub of the band-stop isolator to cover the primary heat-generating regions.

In the thermal analysis, the inlet water temperature is set to 293.15 K, and the convective heat transfer coefficient is taken as 10,000 W/m²/K [46]. Under these boundary conditions, the steady-state temperature distribution of the bimodal cavity operating at the specified conditions is numerically evaluated, as shown in Fig. 12(b). The simulation results indicate that the maximum temperature rise is approximately 42.5 K, and the maximum stress caused by the temperature rise is 50.6 MPa, occurring in the vicinity of the HOM coupling aperture.

The temperature control under full-power input has been analyzed above. Under off-resonance or mismatched conditions, the reflected power at the harmonic-mode coupler increases, following the standard power-flow behavior of a driven cavity. In practice, it is redirected by the circulator to an external load, while the remaining heat is removed by the cooling water.

IV. SUMMARY AND OUTLOOK

Double-rf systems play a key role in longitudinal beam manipulation for advanced storage-ring light sources. To address the demand for compact and integrated rf configurations in medium- and low-energy storage rings, this work proposes an active bimodal rf cavity concept that combines

beam acceleration and third-harmonic operation within a single structure. In the proposed design, the TM_{010} mode is employed as the accelerating mode, while the TM_{020} mode operates as the third-harmonic mode, enabling flexible control of longitudinal beam dynamics within one cavity.

A systematic rf design is performed to realize independent field buildup and frequency tuning for both operating modes. To accommodate the specific constraints of high-order-mode suppression in a bimodal configuration, a selective HOM damping scheme based on waveguide extraction and mode isolation is investigated, demonstrating effective suppression of detrimental HOMs while preserving the rf characteristics of the operating modes. The design and simulation results presented in this work illustrate the potential of bimodal rf cavities as an integrated approach for implementing dual-rf functionalities in compact storage-ring rf systems.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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