

Novel bimodal radiofrequency cavity enabling independent operation and effective higher-order mode damping for high-brightness particle beams

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Developing multifrequency acceleration systems is crucial for optimizing beam dynamics in high-brightness particle beams, particularly for minimizing energy spread, manipulating bunch length, and facilitating beam bunching. This paper introduces a novel bimodal radio frequency (rf) cavity design that integrates both fundamental and harmonic modes within a single structure, offering enhanced spatial efficiency and improved operational flexibility for multifrequency rf systems. Unlike traditional designs, our cavity enables independent and simultaneous operation of each mode, along with effective suppression of higher-order modes (HOMs), which is critical for high-current beam stability. This breakthrough addresses significant challenges in bimodal cavity technology, such as intermode tuning coupling, rf-driving coupling, and effective HOM damping, providing essential solutions for high-current beam applications. Our work opens new research avenues in advanced rf cavity design, with significant implications for the future of high-brightness beam technologies, including advanced accelerator designs and improved beam quality.

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I. INTRODUCTION

Particle accelerators are essential tools in advancing scientific research, industrial applications, and medical technologies [1,2]. A key objective in accelerator design is achieving high-brightness beams, which are crucial for enhancing the resolution and precision of experimental results and improving overall accelerator performance and efficiency. Multifrequency acceleration systems, integrating a combination of fundamental and harmonic cavities, offer promising approaches to optimize beam dynamics by shaping beam bunches, reducing energy spread, and facilitating bunching [3–6]. However, conventional approaches require significant space and resources for radio frequency (rf) cavities with different frequencies, posing

substantial challenges in the spatially constrained environments typical of linear and ring accelerators [7,8].

An effective solution is the development of multimode cavities that integrate both fundamental and harmonic modes within a single structure, thus conserving space and reducing the number of cavities [4,9]. In addition to spatial efficiency, these cavities, depending on their specific designs, have the potential to enhance acceleration efficiency, increase phase acceptance, and elevate rf breakdown thresholds [10–13]. The exploration of multimode cavities spans several decades [14], with recent advancements focusing on their application to improve the performance of rf electron guns and accelerating cavities [15,16]. Despite the straightforward concept and their theoretical advantages, multimode cavities encounter significant technical hurdles, particularly in achieving independent frequency tuning and rf drive, and effectively damping higher-order modes (HOMs), all of which are critical for maintaining beam quality. Traditional bimodal designs, typically based on modified pillbox or elliptical cavities, cannot independently adjust their operating frequencies and face challenges in effectively damping certain HOMs that fall between the two operating frequencies, limiting their practical utility in high-brightness beam applications [10,17].

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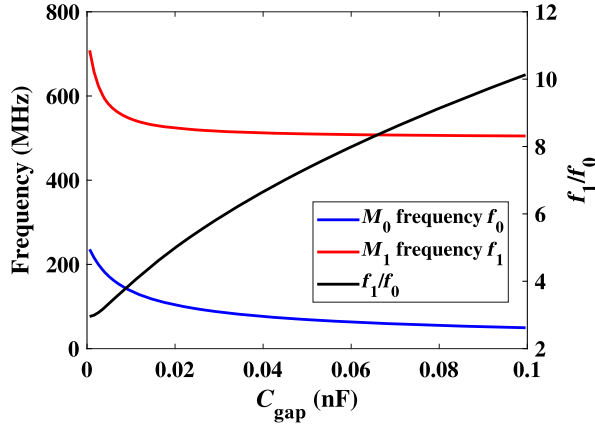


FIG. 1. f_0 , f_1 , and f_0/f_1 as the function of C_{gap} at a Z_0 of $100\ \Omega$.

In this paper, we introduce a novel bimodal rf cavity design utilizing a coaxial structure. This design employs its two lowest monopole modes as accelerating modes, corresponding to the fundamental and harmonic systems. The two accelerating modes can be operated independently, and the frequency ratio between them can be tailored to specific requirements. Moreover, HOMs can be heavily damped. This work represents a significant advancement in bimodal cavity technology, offering a transformative pathway for multifrequency rf systems in high-current particle accelerators.

II. BIMODAL CAVITY DESIGN

Our bimodal cavity design employs a coaxial structure. In a quarter-wave coaxial resonant cavity, the

approximate resonant frequencies are calculated using Eqs. (1) and (2) [18].

$$Z_0 \tan(2\pi f_n L/c) = 1/(2\pi f_n C_{\text{gap}}), \quad (1)$$

$$Z_0 = \sqrt{\mu/\epsilon} 2\pi \log(r_2/r_1), \quad (2)$$

where Z_0 is the characteristic impedance, f_n is the resonant frequency, and n is the mode number. L is the cavity length, c is the speed of light, C_{gap} is the capacitance of the accelerating gap, and r_1 and r_2 are the radii of the inner and outer conductors, respectively. μ and ϵ represent the permeability and permittivity in vacuum, respectively. Solving Eq. (1) illustrates that the ratio between f_0 and f_1 can be adjusted by varying C_{gap} , as depicted in Fig. 1. The electromagnetic field distribution at the acceleration gap exhibits characteristics similar to monopole modes, making them suitable for particle acceleration. Thus, the first two modes, labeled M_0 and M_1 , can be designed as the fundamental and harmonic modes with the desired frequency ratio by selecting an appropriate C_{gap} within a single cavity.

In practical rf cavity design, achieving voltages of several hundred kilovolts or more requires a larger accelerating gap, which results in a very small value of C_{gap} . Two methods can be used to adjust the capacitance: using a capacitor-loaded plate, as demonstrated in [19], or modifying the diameter of the outer conductor, as illustrated in Fig. 2(a). Considering the significant impact of loading capacitors on cavity performance, we opted for the latter approach. To verify our scheme, we designed a normal-conducting bimodal cavity with a fundamental

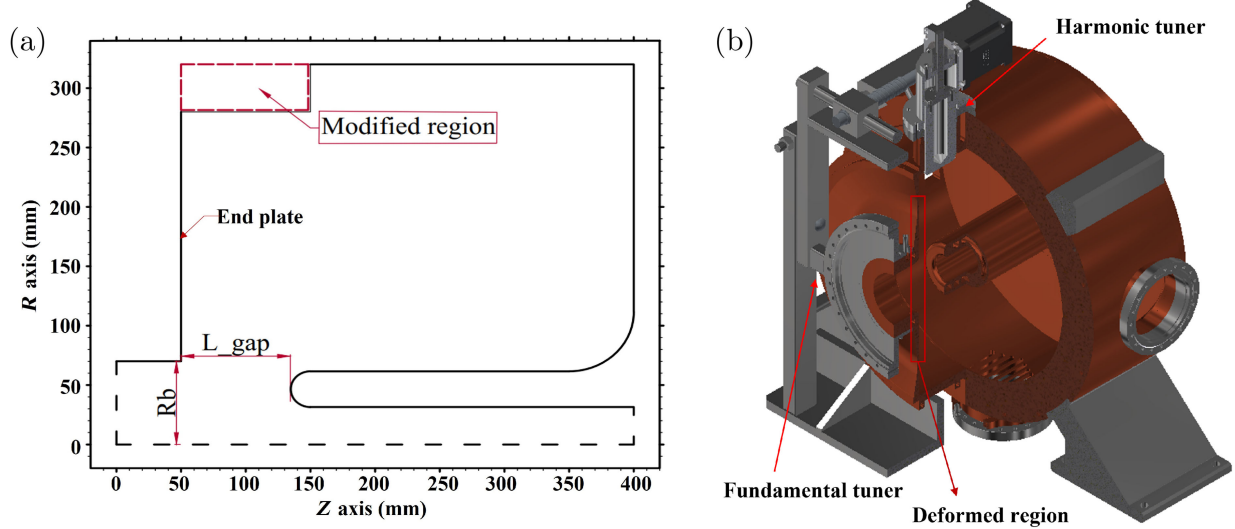


FIG. 2. (a) Bimodal cavity, designed by modifying the outer conductor diameter of the accelerating gap region. (b) Bimodal cavity equipped with dual independent tuning systems: the fundamental frequency is adjusted by axially squeezing the end plate, while the harmonic frequency is regulated using a plunger tuner.

frequency of 166.6 MHz and a third harmonic frequency of 499.8 MHz for synchrotron light sources, as shown in Fig. 2(b).

Several constraints guided our design process. First, to ensure practicality, the outer conductor diameter and length were constrained to be less than 1.0 and 0.5 m, respectively. Second, the frequencies for the fundamental and harmonic modes, corresponding to the two lowest monopole modes of the cavity, were set at 166.6 and 499.8 MHz. Third, to enable effective HOM damping, the frequency of the next monopole mode with high impedance was set to exceed 600 MHz, ensuring significant frequency separation from the operating modes. Fourth, to ensure effective cooling of the cavity, particularly in the inner conductor area, power dissipation was constrained to less than 40 kW at design voltages of 300 kV for the fundamental mode and 180 kV for the harmonic mode.

To achieve independent tuning for the two operating modes, two distinct tuning devices were implemented. The coaxial bimodal cavity exhibits significantly different electromagnetic field distributions for its two operating modes. Figure 3(a) illustrates the radial distribution of electric and magnetic field energy densities for both modes at $Z = 50.5$ mm, near the end plate. According to cavity perturbation theory, as described in Eq. (3), frequency adjustment can be achieved through perturbation when there is a substantial difference between the intensities of the electric and magnetic fields; conversely, perturbation has no effect on the frequency when their intensities are similar [18].

$$\frac{\Delta f}{f_a} = \frac{\int_{V_b} (\mu |\mathbf{H}|^2 - \epsilon |\mathbf{E}|^2) dv}{\int_{V_a} (\mu |\mathbf{H}|^2 + \epsilon |\mathbf{E}|^2) dv}, \quad (3)$$

where f_a is the resonant frequency of the cavity before perturbation, and V_b and V_a denote the volumes of the

perturbation and the cavity, respectively. Calculations reveal that the electric field energy of the fundamental mode in the radial span of 70–188 mm—excluding the 0–70 mm range allocated for beam tubes—greatly exceeds the magnetic field energy. In contrast, the electric and magnetic field energies of the harmonic mode are comparable. Therefore, we designed an end plate with a minimum thickness of 5 mm at a radius of 188 mm to enable controlled deformation, as illustrated in Fig. 2(b). Consequently, the fundamental frequency can be independently tuned by deforming the end plate. To ensure tuning remains within the elastic limit, the maximum mechanical stress on the end plate must remain below 70 MPa. The end plate was fabricated from forged copper and attached to the cavity via electron beam welding. Figure 3(b) illustrates the electromagnetic energy density distribution of these modes at $R = 275$ mm, near the outer conductor, which exhibits a significant difference. Specifically, the harmonic mode exhibits a strong magnetic field and a weak electric field near the end plate, while the fundamental mode displays a relatively uniform electromagnetic field. A plunger-type tuner, strategically installed in this region as shown in Fig. 2(b), can fine-tune the harmonic frequency with minimal impact on the fundamental frequency. The tuner has a diameter of 120 mm and a travel range of 40 mm (from -20 to $+20$ mm), with a maximum insertion depth into the cavity of 20 mm.

To independently control the amplitude and phase of the cavity voltage for the two operating modes, we designed two distinct input couplers. The input coupler for the fundamental mode utilizes a coaxial structure, as shown in Fig. 4(a). To prevent mutual interference between the modes, this coupler is positioned at $Z = 290$ mm, where the magnetic field of the harmonic mode is weakest, as illustrated in Fig. 3(b). Additionally, 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

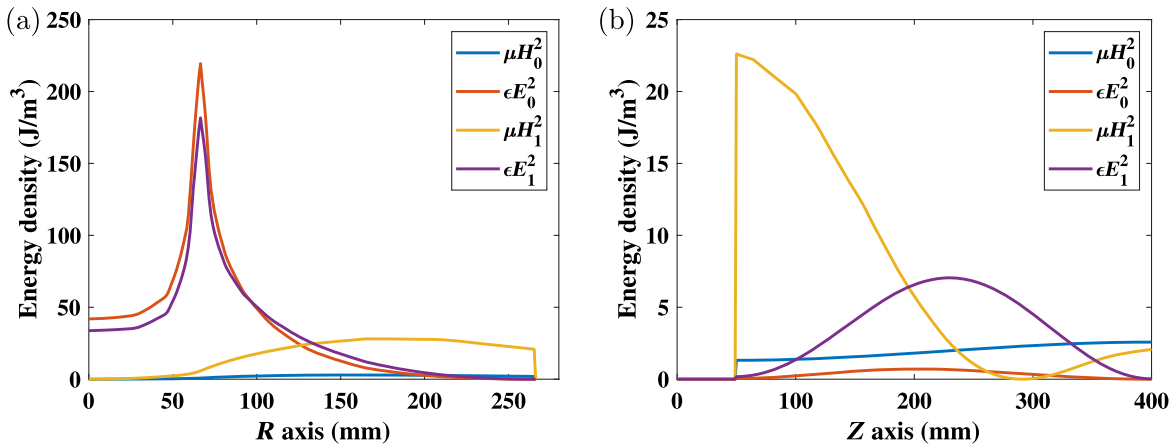


FIG. 3. (a) Radial energy density distribution for the two operating modes at $z = 50.5$ mm, where $z = 50$ mm represents the end plate, each with 1 J of stored energy. (b) Electromagnetic energy density distribution at $R = 275$ mm for the two modes in the axial direction, each with 1 J of stored energy, E_0 and H_0 denote the electric and magnetic field values of the fundamental mode, respectively, while E_1 and H_1 denote those of the harmonic mode.

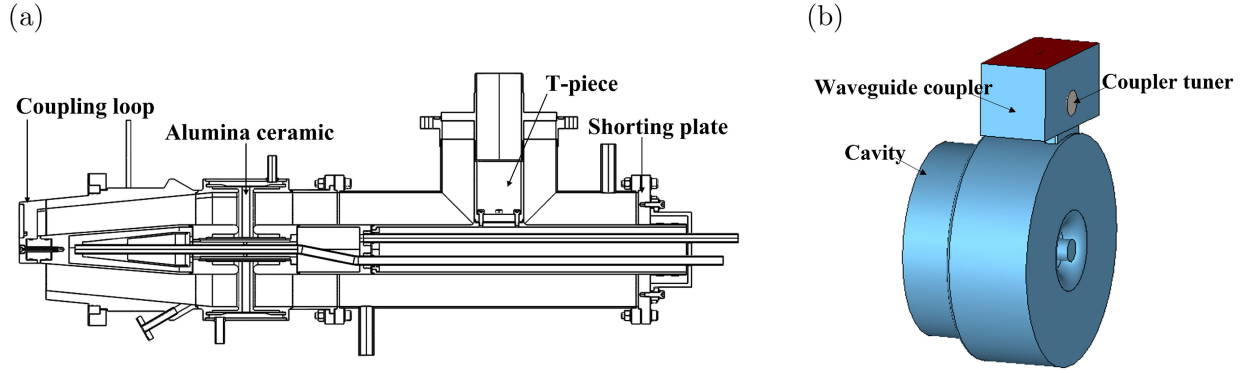


FIG. 4. (a) Cross-sectional view of the fundamental coupler. (b) Bimodal cavity with a WR-1500 waveguide coupler.

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 into the high-power coupler's inner conductor to manage thermal loads. The coupling coefficient can be adjusted by rotating the coupling loop angle. For the harmonic mode, the input coupler employs a WR-1500 waveguide, depicted in Fig. 4(b). The input coupler port is rectangular, measuring 381 by 190.5 mm, and features a rectangular iris measuring 160 by 40 mm in the cavity's common wall. The transmission cutoff frequency of the rectangular waveguide ensures that the input coupler does not couple or transmit power for the fundamental mode, and its coupling coefficient can be adjusted using a plunger-type coupler tuner. Thus, the two input couplers can deliver rf power to each mode independently, without mutual interference.

The coaxial bimodal cavity utilizes the first two monopole modes as accelerating modes, and there are no high-impedance HOMs between them. Both waveguide-type couplers (e.g., BESSY 500 MHz HOM-damped cavity [20]) and antenna-type HOM absorbers (e.g., MAX IV cavities [21]) can be used to suppress these HOMs. However, waveguide-type couplers significantly impact the performance of the operating modes, whereas antenna-type HOM absorbers struggle to achieve heavy HOM damping. Therefore, in this study, we adopted a beam absorber, which is easier to implement and provides stronger HOM damping. 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 [22]. 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 [23]. The absorber employs ferrite as the absorbing material and has a diameter of 380 mm. A cavity iris with a diameter of

140 mm and a transition section of 200 mm length are designed to allow HOM propagation while effectively preserving the accelerating modes, as shown in Fig. 5. Simulation results demonstrate that the total power loss absorbed by the ferrite absorber for the two modes is less than 400 W when operating at the full design power level of 40 kW. The impedance of the first accelerating mode is reduced by less than 0.1%, and the second mode by 2%, due to the influence of the beamline HOM absorber. Taking into account beam-induced HOM power, the ferrite absorber is engineered to handle a maximum power absorption of 5 kW. The cooling system is meticulously designed to ensure that the ferrite temperature remains below 55 °C, with a permissible temperature increase of 30 °C, which is considered acceptable for operational stability [24,25]. CST Particle Studio and CST Microwave Studio [26] were employed for the multipacting simulation of the bimodal cavity. The argon-discharged copper, equivalent to the copper material after high power conditioning [27], 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.

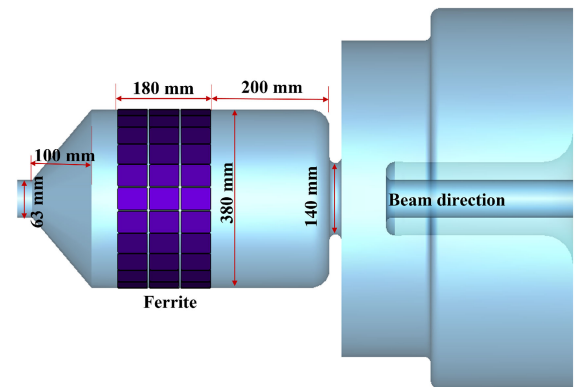


FIG. 5. Bimodal cavity with a beamline HOM absorber.

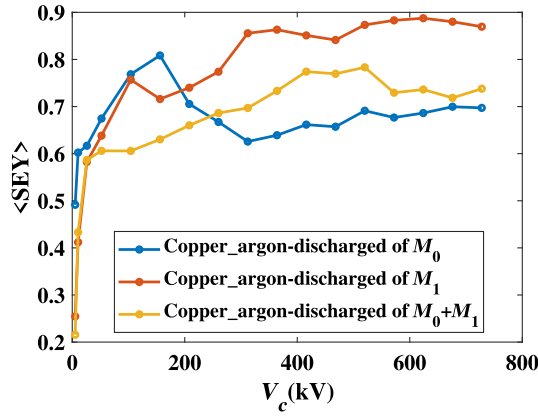


FIG. 6. Maximum $\langle \text{SEY} \rangle$ for all regions of the fundamental, harmonic, and combined modes of the bimodal cavity after high power conditioning, as simulated by using argon-discharged copper.

The rf electromagnetic field map for both fundamental and harmonic modes, calculated via the eigenmode solver, was imported into the particle-in-cell solver. Simulations were conducted over 12 rf phases (in 30° increments) and accelerating voltages from 25 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 ($\langle \text{SEY} \rangle = \text{Total Secondaries} / \text{Total Impacts}$) [28]. As depicted in Fig. 6, the maximum $\langle \text{SEY} \rangle$ for all regions of the fundamental, harmonic, and combined modes consistently remained below the critical threshold of 1.0, indicating effective multipacting suppression.

The mechanical design focus was on the fundamental frequency tuning mechanism and the thermomechanical

characteristics of the main structure. Fundamental frequency adjustment is accomplished by mechanically compressing the cavity's end plate. Achieving the frequency tuning range of 166.6 ± 0.25 MHz necessitates a 1 mm deformation at the end plate. Simulations indicate that achieving maximum deformation of 1 mm requires applying either 7.5 kN of pressure or 8.5 kN of tension. Including thermal stress contributions, the maximum mechanical stress at the end plate remains below 70 MPa, as illustrated in Fig. 7(a). The cooling system is engineered to support a maximum cavity power capacity of 40 kW, corresponding to operating voltages of 300 kV for the fundamental and 180 kV for the harmonic modes. Based on the average power loss density across the cavity inner surfaces, the design includes 12 cooling pipes for the cavity mantle, 2 for each end plate, and 2 spiral-shaped pipes for the inner conductor. Thermal simulations confirm that maximum cavity temperature stays under 50° , as shown in Fig. 7(b). 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, these thermal-induced frequency changes remain within acceptable limits.

III. TESTING RESULTS AND DISCUSSION

We successfully constructed a bimodal cavity using oxygen-free high-conductivity copper. The primary parameters and measured results are outlined in Table I. The fundamental mode exhibits a resonance frequency of 166.6 MHz, while the second monopole mode, functioning

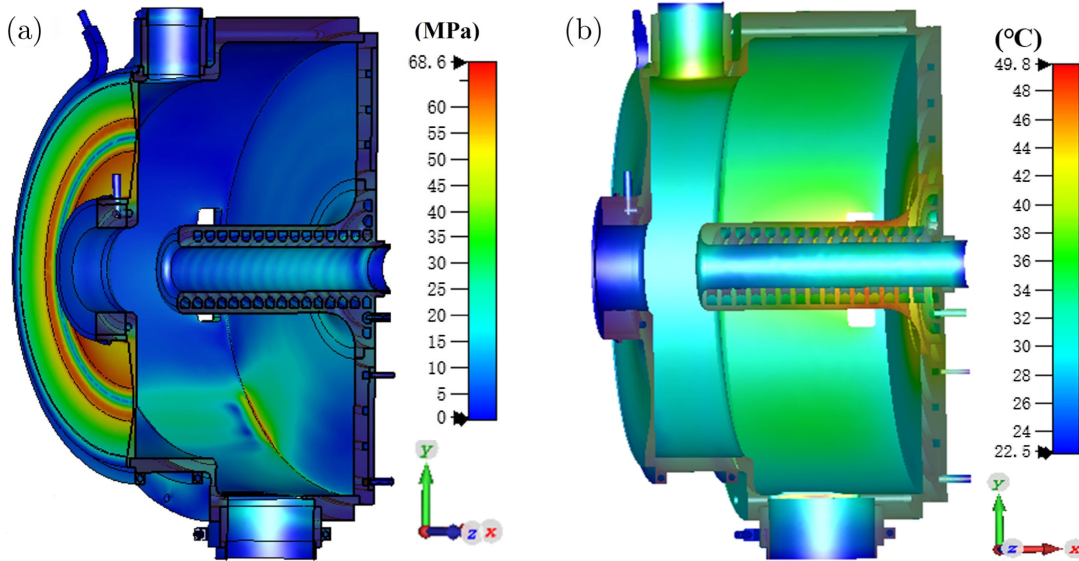


FIG. 7. (a) Distribution of stress across the cavity resulting from the combined effects of thermal expansion and maximum tuning force. (b) Temperature distribution across the cavity under a power dissipation of 40 kW.

TABLE I. Main parameters of the bimodal cavity.

Parameter	Design values		Measured values	
	M0	M1	M0	M1
Frequency (MHz)	166.67	499.8	166.63	499.76
Shunt impedance (M Ω)	5.71	1.83	5.32	1.72
R/Q (Ω)	228	47.7	226	48
Unloaded quality factor Q	25,000	38,400	23,540	35,780

as the third harmonic, resonates at approximately 499.8 MHz. The unloaded quality factors for the two modes were measured at 22,400 and 34,600, respectively, achieving over 93% of their corresponding simulated values. The electromagnetic field distribution for both operating modes was assessed using the bead-pull method [29]. Figure 8 illustrates a comparison between

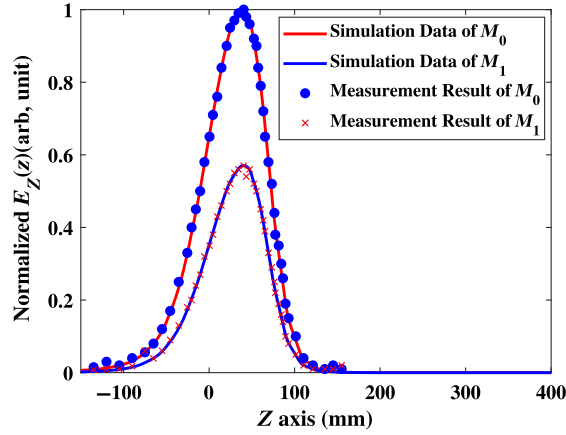


FIG. 8. Comparison between the simulated longitudinal field distribution of the two accelerating modes along the beam axis for the bimodal cavity and the experimental result of the bead-pull measurement.

the simulated longitudinal field distributions of the two accelerating modes along the beam axis and the corresponding experimental results obtained from the bead-pull measurement, indicating the test results agree well with the simulation results. The R/Q values and shunt impedance are derived from bead-pull measurement results. The measured R/Q values for the two modes are 226 and 48 Ω , with effective shunt impedance of 5.32 and 1.72 M Ω , respectively.

A frequency tuning range of 166.6 ± 0.25 MHz was achieved for the fundamental mode through a ± 1 mm deformation of the endplate. It requires a pressure of 7.2 kN or a tension of 8.5 kN to compress or extend the tuning mechanism, respectively. Measured tuning sensitivity is approximately 270 kHz/mm for the fundamental mode and 3 kHz/mm for the third harmonic mode, as depicted in Fig. 9(a). The influence of tuning the fundamental mode on the harmonic frequency is minimal, less than 0.5%, which is consistent with simulation results. The use of a tuner plunger achieved a tuning range of ± 500 kHz for the harmonic. The tuning sensitivities are approximately 30 kHz/mm for the harmonic mode and 0.5 kHz/mm for the fundamental mode, as shown in Fig. 9(b). The effect of harmonic tuning on the fundamental frequency is under 2%, aligning with simulation predictions.

Normal-conducting rf cavities typically exhibit a bandwidth of several kHz, while frequency deviations due to temperature fluctuations (after reaching thermal equilibrium) are generally within a few hundred Hz. In advanced accelerators, rf systems generally maintain phase control accuracy to within approximately 0.1° . A phase error magnitude increasing to 1° —1 order of magnitude greater than typical control precision—can lead to significant beam quality degradation, potentially resulting in beam loss. For this bimodal cavity, the loaded-quality factors span approximately 5000 to 15,000 for the fundamental mode and 10,000 to 20,000 for the harmonic mode. According to

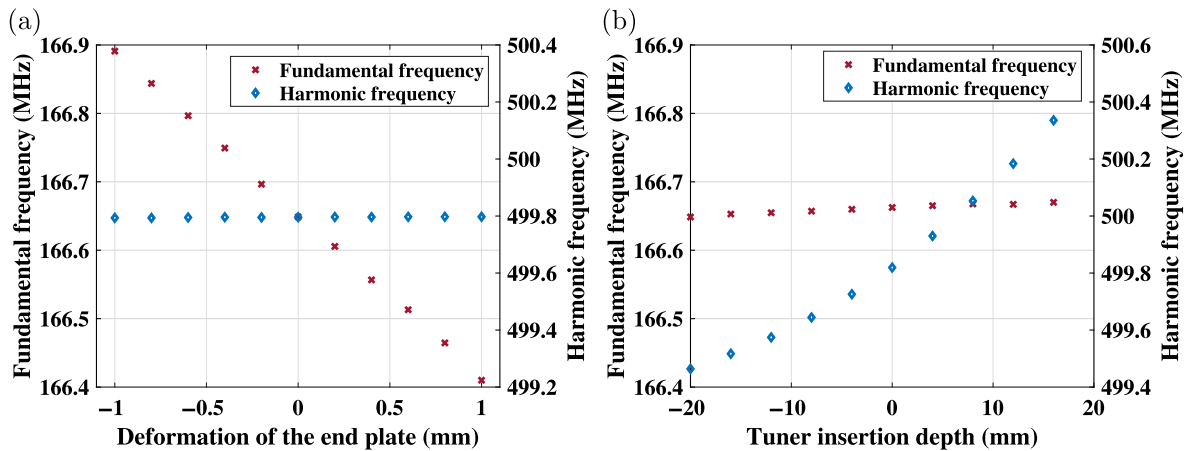


FIG. 9. Measured results of the two tuning devices: (a) variation in operating frequencies due to deformation of the end plate. (b) Variation in operating frequencies as a function of plunger insertion depth.

Eq. (4), if the phase error reaches 1° , the frequency error for the harmonic mode will remain below 436 Hz.

$$\tan(\Delta\phi) = \frac{2Q_L\Delta f_c}{f_c}, \quad (4)$$

where $\Delta\phi$ is phase error, Q_L is loaded-quality factor, Δf_c is frequency error, and f_c is resonant frequency. The impact of the harmonic frequency adjustment by 436 Hz on the fundamental frequency remains within the allowable range of fundamental frequency control errors. Therefore, the two tuning devices, with mutual influence under 2%, enable independent frequency tuning by operating each tuner individually. When the mutual influence between the tuners is below 15%, independent frequency control can be achieved by operating both tuners simultaneously. However, if the mutual influence exceeds 15%, multiple iterative adjustments may be necessary. Given that the response times of tuning are on the order of milliseconds, achieving rapid tuning in some scenarios may be challenging.

The coupling and transmission characteristics of the input couplers were evaluated using a vector network analyzer while mounted on the cavity. The measured reflection coefficients for the two input couplers, with coupling factors set to 1.0, were both less than -30 dB, indicating effective transmission of both fundamental and harmonic power to the cavity. With the fundamental coupler's coupling factor set to 1.0, the transmission coefficient S21 from the fundamental coupler to the harmonic coupler was assessed at various coupling factors of the harmonic coupler. As shown in Fig. 10(a), S21 is less than -30 dB, indicating that the harmonic coupler minimally couples fundamental power, at less than 0.1%. The effect of the fundamental coupler on the harmonic mode performance was evaluated using the same method, with

results in Fig. 10(b) showing S12 is less than -40 dB. Consequently, the two input couplers can independently supply power to the two operating modes without interference. Notably, adjusting the coupling factor of the fundamental input coupler by rotating the coupling ring causes various perturbations to the harmonic electromagnetic field and slightly alters the third harmonic resonance frequency by less than 60 kHz, necessitating frequency adjustments through the tuner during normal operation.

The HOMs of the bimodal cavity, both with and without the HOM absorber, were investigated through a systematic three-step process. First, the HOM impedance spectrum was simulated using CST Microwave Studio and Particle Studio. Second, the field distributions of these high-impedance HOMs were obtained via the bead-pull method and compared with the simulated results to accurately identify the modes [30]. Finally, the impedance of each mode was determined by independently measuring R/Q and Q and computing their product. The measured results of the main longitudinal and transverse HOM impedances, both with and without the HOM absorber for the bimodal cavity, are shown in Figs. 11(a) and 11(b), which are consistent with the simulation results. The results indicate that the longitudinal HOM impedances are below 4.0 k Ω , and the transverse HOM impedances are below 70 K Ω /m when the beamline HOM absorber is used, achieving an advanced level of HOM-damped normal-conducting cavities [20,31].

The experimental results validate the feasibility of the bimodal rf cavity, enabling independent operation for both modes and effective HOM damping. The fundamental mode's shunt impedance measures 5.32 M Ω , significantly exceeding that of traditional coaxial rf cavities with a single accelerating mode, which typically have a shunt impedance of approximately 3.4 M Ω [19,32]. In such cavities, the first monopole HOM often resonates at a frequency close to that

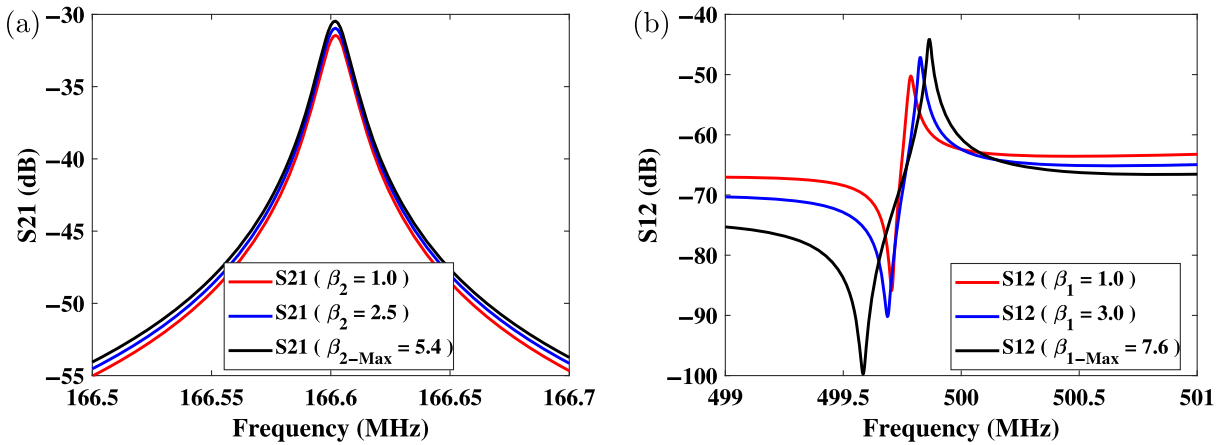


FIG. 10. (a) Transmission coefficient S21 from the fundamental coupler to the harmonic coupler for various coupling factors of the harmonic coupler, while the fundamental coupler's coupling factor is set to 1.0. (b) Transmission coefficient S12 from the harmonic coupler to the fundamental coupler for various coupling factors of the fundamental coupler, while the harmonic coupler's coupling factor is set to 1.0.

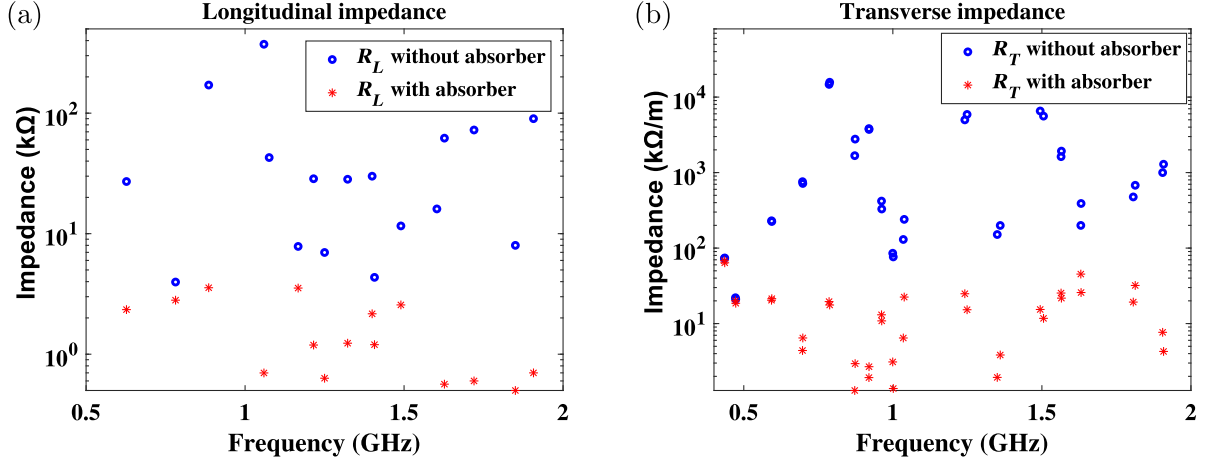


FIG. 11. (a) Measured values of the longitudinal HOM impedance with and without the HOM absorber. (b) Measured values of the transverse HOM impedance with and without the HOM absorber.

of the fundamental mode, and suppressing this HOM typically compromises accelerating performance. Our bimodal cavity, however, repurposes this previously problematic monopole HOM as an operational mode, thereby enhancing the performance of the fundamental mode. The harmonic impedance of the bimodal cavity is $1.72\text{ M}\Omega$, which is lower than the typical $5\text{ M}\Omega$ for a single harmonic cavity at the same frequency [19]. However, in practical applications, more fundamental cavities are typically required compared to harmonic cavities, so the cumulative harmonic impedance provided by the bimodal cavity scheme can match that of conventional separated cavities. Moreover, because the harmonic voltage is divided and cavity dissipation power scales with the square of the voltage, the total harmonic cavity loss can be reduced. The bimodal cavity is equipped with two input couplers to independently control the amplitude and phase of the two voltages. In many cases, the harmonic system is passive and does not require harmonic couplers, making the bimodal cavity more concise and advantageous. To achieve deep suppression of high-order modes, our bimodal cavity adopts a beam absorber, which requires sacrificing some longitudinal space. If the requirement for HOM damping is less stringent, antenna-type HOM absorbers can be used, resulting in a more compact structure. Consequently, this bimodal cavity is particularly well suited for compact accelerators requiring dual-frequency rf systems, such as advanced synchrotron light source storage rings [7,17], linear accelerators incorporating dual-frequency bunchers for beam shaping [5,33], dual-frequency electron guns operating in the very high-frequency range (30–300 MHz) [16,34], among others. However, the coaxial structure of this bimodal cavity is less suitable for applications with a fundamental frequency greater than 1.5 GHz due to its reduced size and increased power density. This poses significant manufacturing and thermal challenges, particularly in the inner conductor region. Furthermore, rf structures

operating above 1.5 GHz often require multicell configurations to achieve sufficient voltage gain. However, the coaxial design struggles with implementing these configurations due to the difficulties in achieving effective coupling between cells.

IV. CONCLUSION

In summary, we have successfully developed a novel bimodal rf cavity that overcomes the longstanding challenges of achieving independent operation and effective HOM damping, marking a significant advancement in the design of bimodal rf cavities. This design utilizes a coaxial structure, employing its two lowest monopole modes as fundamental and harmonic modes within a single cavity. This approach optimizes spatial efficiency and reduces the number of cavities, establishing the bimodal cavity as a compact and cost-effective solution for modern accelerator systems.

Our experimental results demonstrate high performance, with measured parameters closely matching design values. The tuning mechanisms and input couplers enable independent operation of the two modes, ensuring optimal performance under varying conditions. Furthermore, the integration of a beamline HOM absorber effectively suppresses unwanted modes, making the cavity suitable for high-current accelerator applications. This advancement opens new avenues for designing multifrequency rf systems, contributing to the development of high-brightness beams and enhancing the capabilities of future accelerator technologies. It offers a viable solution for accelerator applications that demand high efficiency and compact design.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [22].

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