Selective Suppression of TM_{020} Mode Leakage in Damped Cavities via Integrated Narrowband Filter

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Abstract

TM020 mode damped cavities enable compact accelerators but suffer from severe electromagnetic field leakage arising from coupling slot misalignment and structural asymmetry. We propose an integrated narrowband filter based on RLC circuit design that selectively suppresses TM020 leakage while preserving higher-order mode damping. Critically, the filter reduces electromagnetic field leakage to below 0.6%—more than one order of magnitude lower than unfiltered cavities (>4%)—and increases positional tolerance by a factor of four ($±$0.8 mm versus $±$0.2 mm). Impedance spectroscopy confirms minimal impact on higher-order mode damping.

Under 20 kW power, thermomechanical analysis demonstrates exceptional stability: peak temperature rise $ $21.3 K, frequency detuning $ $0.182 MHz, with leakage increasing only to 0.65% (still six times lower than the unfiltered baseline). This design resolves the critical leakage-robustness tradeoff in next-generation synchrotrons.

Full Text

Preamble

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Abstract

The TM020 mode damped cavity enables compact accelerator designs but suffers from severe electromagnetic field leakage arising from coupling-slot misalignment and structural asymmetry. We propose an integrated narrowband filter based on RLC circuit design to selectively suppress TM020 leakage while preserving higher-order mode damping. The filter reduces electromagnetic field leakage to below 0.6%—more than an order of magnitude lower than unfiltered cavities (>4%)—and increases positional tolerance fourfold ($±$0.8 mm versus $±$0.2 mm). Impedance spectra confirm minimal impact on higher-order mode damping. Under 20-kW operation, thermo-mechanical analysis demonstrates exceptional stability: peak temperature rise $ $21.3 K, frequency detuning $ $0.182 MHz, and leakage increase to only 0.65% (still six times lower than unfiltered baselines). This design resolves the critical leakage-robustness trade-off in next-generation synchrotrons.

Keywords: TM020 mode damped cavity, Electromagnetic field leakage, Integrated narrowband filter, RLC circuit design, Thermo-mechanical stability

1. Introduction

The relentless pursuit of ultralow emittance and diffraction-limited performance in fourth-generation synchrotron light sources intensifies beam dynamics challenges. While multi-bend achromat lattices enable emittances below 100 pm · rad, the resultant high electron density exacerbates intrabeam scattering, degrading both emittance and Touschek lifetimes [1, 2]. Double-radiofrequency (RF) systems employing harmonic cavities to lengthen bunches offer a critical solution [3]. However, conventional normal-conducting (NC) harmonic cavities operating in TM010 modes face inherent limitations: their high shunt impedance per unit length (R/Q) and susceptibility to transient beam-loading during bunch gap modulation compromise voltage stability, particularly at 1.5 GHz [4, 5]. Although superconducting cavities mitigate some issues, their cryogenic complexity and cost drive demand for innovative NC alternatives [6].

The TM020 mode damped cavity emerges as a pivotal NC solution that addresses transient beam-loading, coupled-bunch instabilities (CBIs), and compactness requirements. Unlike TM010 mode cavities, the TM020 mode exhibits a unique electromagnetic field distribution with a radial magnetic node, enabling compact embedded damping structures (e.g., coaxial slots, rod-type couplers) that suppress parasitic modes while preserving high Q_0 and low R/Q for the accelerating mode [7, 8, 9]. This characteristic is essential for voltage stability in next-generation storage rings [4].

The viability of TM020 mode cavities has been demonstrated in several projects.

Pioneering work by Ego et al. validated TM020 mode cavities in the SPring-8-II project, achieving a shunt impedance of 6.8 MΩ and effective parasitic mode damping through circumferential slots lined with microwave absorbers [10]. Subsequent studies by KEK optimized cavity geometries, revealing that axial symmetry and precise placement of damping structures (e.g., ferrite-loaded slots) are crucial for minimizing power leakage from the TM020 mode [7]. Low-power measurements confirmed resonant frequency agreement within 270 kHz of simulations and validated the effectiveness of threefold-symmetric tuners in reducing Q_0 degradation [11]. High-power prototypes tested at SPring-8 demonstrated stable operation at 120 kW with 900 kV accelerating voltage, albeit highlighting challenges in thermal management and frequency stability under beam loading [12]. The Thailand New Light Source (SPS-II) and KEK Light Source (KEK-LS) projects further advanced TM020 applications, achieving shunt impedances of 8.3 MΩ (main cavity) and 2.45 MΩ (harmonic cavity) while suppressing parasitic modes to loaded Q values below 1,000 [7, 13].

A critical challenge persists: electromagnetic field leakage from the accelerating TM020 mode into damping structures. As shown in Fig. 1a [Figure 1: see original paper], even minor coupling-slot misalignment (ΔR = $±0.2mm)orsymmetry−breakingstructures(e.g., couplers)shiftthesensitivemagneticnodeposition(Fig.1b), i
(30,500) and reduce ferrite power density near safety limits but increase cavity length by 80 mm and impair damping efficiency (Fig. 2 [Figure 2: see original paper]) [15]. Coupler compensation topologies reduce leakage to 0.18% but fail to address beam-induced node shifts or transient heating [16]. Balancing deep leakage suppression, unimpeded higher-order modes (HOMs)/lower-order modes (LOMs) damping, and mechanical compactness remains unresolved.

In this Letter, we present a new approach that resolves this long-standing conflict by integrating a frequency-selective narrowband filter directly into the damping structure. This filter functions as a highly reflective mirror at the precise frequency of the TM020 accelerating mode (1.5 GHz) while remaining transparent to the spectrum of other LOMs/HOMs that must be suppressed. Our results show this design dramatically reduces EM leakage by over an order of magnitude, from a baseline exceeding 4% to less than 0.6%. Crucially, this is achieved with negligible impact on the impedance of other modes, preserving the cavity' s essential damping characteristics across the frequency spectrum. Furthermore, the filter enhances system robustness, increasing the positional tolerance for the coupling slot by a factor of four. This integrated filter design overcomes a key obstacle for next-generation high-performance accelerator cavities, ensuring structural integrity and stable operation under high power.

Fig. 1. Analysis of problems leading to EM field leakage in the TM020 mode. (a) TM020 mode damped cavity structure, where R is the distance from the coupling slot center to the axis. (b) Introduction of couplers breaks the rotational symmetry of the EM field. In cylindrical coordinates, R is the radial parameter of the coordinate point (R, 0, 0), while R_0 represents the cavity radius. (c) Effect of coupling slot position offset on EM field leakage, where ΔR

represents the coupling slot position offset.

Fig. 2. Choke structure scheme analysis. (a) Choke structure. (b) Transmission efficiency analysis, where the green curve shows coaxial structure transmission efficiency, the blue curve shows choke structure transmission efficiency, the black square marks the RF cavity monopole mode, and the red dot marks the dipole mode.

2. Narrowband Filter Design

This section details the design methodology for the coaxial narrowband filter, beginning with foundational RLC equivalent circuit principles. The process involves deriving fundamental resonance characteristics from an analytical model, translating lumped-element parameters into a distributed microwave structure, and performing multi-objective optimization considering both electromagnetic performance and practical mechanical constraints.

2.1. RLC Circuit Foundations and Transmission Analysis

The filter design originates from rigorous analysis of a parallel LC resonator's transmission characteristics. The model, shown in Fig. 3a [Figure 3: see original paper], utilizes a hybrid topology combining distributed transmission line sections with a lumped LC tank circuit. Signal transmission through this composite structure is systematically evaluated using the ABCD-matrix formulation:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos\beta l_1 & jZ_0\sin\beta l_1 \\ jY_0\sin\beta l_1 & \cos\beta l_1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ j\omega C_1 + \frac{1}{j\omega L_1} & 1 \end{pmatrix} \begin{pmatrix} \cos\beta l_2 & jZ_0\sin\beta l_2 \\ jY_0\sin\beta l_2 & \cos\beta l_2 \end{pmatrix}$$

where $\beta = \omega/c$ is the phase constant, and $Z_0 = 1/Y_0 = 50\ \Omega$ is the characteristic impedance of the transmission line sections. The forward transmission coefficient, S_{21}, is derived by converting the ABCD-matrix:

$$S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D}$$

This model predicts two distinct operational regimes, as illustrated by the RLC curve in Fig. 3d. First, the LC tank creates a resonant suppression band centered at frequency $f_0 = 1/(2\pi\sqrt{L_{1C}1})$, producing a sharp rejection notch with over 30 dB attenuation. Second, the transmission lines form a primary passband, acting as a broadband impedance transformer that allows over 90% power transmission for HOM frequencies. To achieve the desired protection for the TM020 mode at $f_0 = 1.5$ GHz, the product of inductance and capacitance is constrained to $L_{1C}1 = (2\pi f_0)^{-2} \approx 1.13 \times 10^{-20}$ H · F. The analysis also shows that the 3-dB bandwidth, Δf, is inversely proportional to the quality factor Q

and can be narrowed by increasing capacitance C_1 while maintaining the $L_{1C}1$ product constant.

2.2. Realization as a Coaxial Microwave Structure

The microwave implementation (Fig. 3b [Figure 3: see original paper]) employs a ceramic-loaded coaxial structure that transforms lumped elements into distributed parameters. The annular ceramic between inner (radius r_i) and outer (radius r_o) conductors (gap $d_0 = r_o - r_i$) provides distributed capacitance (C_{dist}), while copper rings contribute inductance (L_{dist}). From transmission line theory:

$$L_{\text{dist}} = \frac{\mu_r \mu_0}{2\pi} l_c \ln\left(\frac{r_i + d_c + d_1}{r_i + d_c}\right)$$

$$C_{\text{dist}} = 2\pi \varepsilon_r \varepsilon_0 \frac{l_c}{\ln\left(\frac{r_i + d_c + d_1}{r_i + d_c}\right)}$$

$$L_{\text{dist}} \cdot C_{\text{dist}} = \mu_r \varepsilon_r \frac{l_c^2}{c^2}$$

where $c = 1/\sqrt{\mu_0 \varepsilon_0}$ is the speed of light in vacuum, ε_r is the ceramic relative permittivity, l_c is the axial length of the ceramic ring, d_c is the radial thickness of the ceramic ring, d_1 is the radial thickness of the copper ring, and μ_r is the material relative permeability (copper exhibits $\mu_r = 1$ due to its non-magnetic properties).

The RLC equivalent circuit assumes lumped parameters ($L \ll \lambda/4$), whereas actual microwave structures feature distributed EM fields. Particularly at the interface between the copper ring and inner conductor, fringing fields and HOM coupling cause theoretical formulas to underestimate actual inductance or capacitance. This underestimation is addressed through an enhanced lumped-element modeling approach incorporating corrections for distributed capacitance and inductance plus compensation for edge effects, establishing a fringing field correction factor:

$$L'_{\text{dist}} \cdot C' = k \cdot \mu_r \varepsilon_r \frac{l_c^2}{c^2}\left(1 + \alpha \frac{d_c}{\lambda} + \beta \tan\delta\right)$$

where α and β are coefficients calibrated through simulation, and $\tan(\delta)$ is the dielectric loss tangent of the ceramic ring.

The TM020 mode resonant frequency is 1.5 GHz. To meet this requirement, parameters r_i, d_c, d_1, l_c, and ε_r are adjusted to satisfy the $L'_{\text{dist}} \cdot C'$ product of 1.13×10^{-20} H • F, with the inner conductor radius r_i determined by the coupling slot position. The copper ring uses highly elastic beryllium copper C17200 (Poisson's ratio ~ 0.31, electrical conductivity $\sim 25\%$ IACS), providing sufficient equivalent inductance while securing the ceramic ring. Given the coupling slot width d_0 is only 8 mm, the copper ring thickness d_1 is set at 1 mm.

Equation (6) shows that for a given narrowband center frequency, ε_r and l_c^2 are inversely proportional—higher ε_r permits shorter ceramic ring length. Considering TM020 mode damping cavity compactness, the coupling slot length is controlled at 40 mm. To ensure installation space for the narrowband filter structure, the ceramic ring length l_c must be limited to 25 mm, which requires increasing the ceramic node length. Meanwhile, considering the poor thermal conductivity of ceramic materials, the ceramic ring thickness must be controlled within 1 mm. The model shown in Fig. 3b was established and optimized using CST Microwave Studio. With parameters $r_i = 123$ mm, $d_c = 0.8$ mm, $d_1 = 1$ mm, $l_c = 22.2$ mm, and $\varepsilon_r = 30$, the narrowband filter center frequency is 1.5 GHz and the S_{21} transmission curve appears in Fig. 3d.

Further analysis of Fig. 3d reveals that the S_{21} transmission curve for the RLC equivalent circuit differs from the microwave structure' s transmission curve. Specifically, the narrowband filter structure periodically exhibits multiple notches. The ceramic ring and copper ring design may excite HOMs (e.g., third/fifth harmonics) in addition to the TM020 mode frequency (1.5 GHz), where n is the stopband order. The 3.0 GHz operational frequency, situated below the beam pipe' s TM01 mode cutoff (3.645 GHz for 63 mm diameter) yet above the TE11 cutoff (2.791 GHz), requires strategic avoidance of HOM resonant frequencies at this spectral position to ensure unimpeded HOM propagation toward absorbing components.

2.3. Fabrication-Oriented Optimization

To address fabrication challenges, high costs, and structural vulnerabilities associated with solid annular ceramic rings, the design was revised to a polygonal configuration using modular square ceramic elements (Fig. 3c [Figure 3: see original paper]). This practical design facilitates manufacturing and assembly. Ceramic pieces are secured within a recess machined on the inner conductor and stabilized by a corresponding polygonal inner surface on the copper clamp ring. Ceramic piece specifications are: width $l_0 = 15$ mm, thickness $d_c = 0.8$ mm, insertion length into inner conductor $d_d = 0.4$ mm, and 6 mm spacing between ceramic pieces. The ceramic ring length l_c was further optimized using CST Microwave Studio.

This revised structure was optimized for compactness and performance. To maintain filter length (l_c) under the 25 mm constraint, a trade-off between l_c and relative permittivity (ε_r) was analyzed, as higher ε_r permits shorter length. For example, increasing ε_r from 30 to 40 reduces required l_c from 22.5 mm to 19 mm. However, simulations showed that $\varepsilon_r = 40$ introduced additional spurious responses into the passband, potentially interfering with HOM transmission and damping. Therefore, $\varepsilon_r = 30$ was selected as optimal.

Finally, a parametric scan of key structural dimensions (l_c, ε_r, d_c) assessed manufacturing tolerances. The analysis indicated that ceramic ring length l_c is the most suitable parameter for fine-tuning during fabrication to precisely correct the filter' s center frequency, with machining allowance reserved for this purpose.

3. Analysis of the TM020 Mode Damped Cavity with Narrowband Filter

This section evaluates the performance of the TM020 mode damped cavity after integrating the optimized narrowband filter. The analysis demonstrates the filter' s effectiveness in suppressing TM020 mode leakage, confirms its selectivity by assessing impact on other modes, and validates the design' s robustness under high-power operational conditions.

3.1. Impact of Narrowband Filter Structures on TM020 Mode

The integrated narrowband filter fundamentally suppresses EM field leakage from the TM020 accelerating mode. As illustrated in Fig. 4a [Figure 4: see original paper], the filter is positioned adjacent to the main cavity to ensure strong coupling. Performance improvement is significant, as shown in the comparative analysis of Fig. 4b. Without the filter, the cavity is highly sensitive to manufacturing tolerances; the minimum achievable leakage rate exceeds 4%, and a coupling slot deviation of just $±$0.2 mm increases this value to 6%. With the filter loaded, the minimum leakage rate is reduced by nearly an order of magnitude to below 0.6%. Furthermore, the filter enhances robustness against mechanical imperfections–leakage remains below 2% even for substantial coupling slot offsets of $±0.8mm, representingafourfoldincreaseintolerablepositionaltolerancecomparedtotheunfilteredcavity.The
seeoriginalpaper]).Table1summarizeshigh−frequencyRFparametersunderoptimalconditions, providingdef
from 4.2% to 0.6% while causing negligible changes to cavity resonant frequency and R/Q. These results establish the filter as an essential component for achieving deep suppression of TM020 mode leakage and creating a design insensitive to coupling perturbations.

Fig. 4. Analysis of EM field leakage in TM020 mode damped cavity under narrowband filter influence. (a) Structural diagram of TM020 mode damped cavity loaded with narrowband filter structure. (b) Comparative analysis of coupling slot position offset impact on EM field leakage under loaded and unloaded narrowband filter conditions. (c) Influence of narrowband filter structure position on EM field leakage.

Table 1: RF parameters of the TM020 mode damped cavity

Parameter	Without Filter	With Filter
freq. [MHz]	3.58$×10^{4}$	3.60$×10^{4}$
R/Q [Ω]		

Parameter	Without Filter	With Filter
Ra [MΩ]		
Pm/Pc [%]		

3.2. Impact on LOMs and HOMs

A critical requirement is that the filter must suppress the TM020 mode without compromising essential cavity damping functions for other modes. The filter' s selectivity is demonstrated by longitudinal and transverse impedance spectra in Fig. 5a [Figure 5: see original paper] and Fig. 5b [Figure 5: see original paper], respectively, comparing cavity impedance with and without the filter. Analysis reveals that filter loading induces only negligible or minor modifications to impedance peaks corresponding to both LOMs/HOMs across the relevant frequency range. The characteristic damping performance provided by the absorber structure for these other modes remains virtually unaffected, as the magnitude and shape of their impedance peaks are largely preserved. This confirms that the filter operates as a highly selective element—it couples strongly to and suppresses the specific TM020 mode while exhibiting weak coupling to other modes. Consequently, the cavity successfully satisfies its dual requirement: achieving deep suppression of the leakage-prone TM020 mode while simultaneously maintaining broadband damping capability for the full spectrum of modes necessary for beam stability.

Fig. 5. Wakefield analysis of the TM020 mode damped cavity, where the red curve corresponds to impedance distribution without the narrowband filter structure, and the black curve represents impedance distribution with the narrowband filter structure implemented. (a) Longitudinal impedance distribution. (b) Transverse impedance distribution.

3.3. High-Power Robustness: Thermal and Mechanical Stability

The filter-enhanced cavity' s viability for practical accelerator applications requires validation of its thermal and mechanical stability under high-power operation. An integrated thermal-mechanical analysis was performed on the mechanical structure shown in Fig. 6 [Figure 6: see original paper].

Thermal analysis (Fig. 7 [Figure 7: see original paper]) was conducted assuming 20 kW power input and 20°C ambient temperature. Results demonstrate effective heat management, with maximum temperature rise confined to 21.3 K at the main cavity nose cone—a region of high field loss. Crucially, temperature rise in the microwave absorber and ceramic filter material (dielectric constant = 20, tan δ = 5\$×10^{-5}\$, thermal conductivity = 26.8 W/mK) is kept below 8 K, preventing excessive thermal stress and preserving material properties.

Subsequent mechanical analysis assessed combined impact of this thermal load and 1.2 atm vacuum stress. As shown in Fig. 8 [Figure 8: see original paper], von Mises stress in copper components and first principal stress in the ceramic remain well below material yield strengths, ensuring structural integrity. Resulting mechanical deformation is quantified on the micrometer scale.

Finally, the effect of these thermo-mechanical deformations on cavity RF performance was evaluated. As detailed in Table 2 , deformations induce negligible frequency detuning of only -182 kHz. While EM field leakage rate increases slightly from 0.60% to 0.65% under deformed conditions, this value remains more than six times lower than the minimum leakage achievable without the filter and is operationally acceptable. Furthermore, since mechanical deformation magnitude is primarily on the micrometer scale and the filter structure was intentionally designed for weak coupling with lower- and higher-order modes to preserve their damping, it is reasonable to conclude that these minute structural changes will have even less significant impact on broadband impedance of other modes. Therefore, damping efficiency for parasitic modes is considered robust and negligibly affected by deformation. These results conclusively demonstrate that the integrated filter design maintains exceptional electromagnetic performance under 20 kW operation while exhibiting robust thermal and mechanical stability.

Fig. 6. Mechanical structure design drawing of narrowband filter type TM020 mode damped cavity.

Fig. 7. Thermal analysis of the TM020 mode damped cavity. The figure displays temperature distribution of the damped cavity, microwave absorber, and narrowband filter structure under 20 kW input power.

Fig. 8. Mechanical stress and deformation analysis of the TM020 mode damped cavity. (a) Initial condition settings. (b) Schematic diagram of vacuum stress and thermal stress analysis, where ceramic material uses First Principal Stress analysis and copper material uses Von Mises Stress analysis. (c) Mechanical deformation caused by vacuum stress and thermal stress.

Table 2: Changes in RF parameters caused by mechanical deformation

Parameter	Value
freq. [MHz]	5.98$×10^{6}$
Δf [MHz]	-0.91$×10^{5}$
Pm/Pc [%]	
Pm/Pc [%][+]	

[+] The EM field leakage rate after mechanical deformation.

4. Conclusion

We demonstrate a narrowband filter structure that fundamentally solves the EM field leakage problem in TM020 mode damped cavities. By integrating

an RLC-designed coaxial filter, TM020 leakage is suppressed to <0.6%—a >6× improvement over conventional designs—while maintaining broadband HOMs damping (verified via longitudinal/transverse impedance spectra). The filter grants unprecedented robustness, tolerating $±$0.8 mm coupling-slot offsets while maintaining leakage below 2%. High-power validation (20 kW) confirms exceptional thermo-mechanical-electromagnetic stability: peak temperature rise $ $21.3 K, mechanically-induced frequency shift $ $0.182 MHz, and leakage increase to merely 0.65%. This performance, achieved without cryogenics or significant cavity lengthening, satisfies the dual requirements of leakage immunity and power resilience for fourth-generation light sources. The design methodology is applicable to superconducting cavities and multi-frequency systems, enabling compact, high-intensity accelerators.

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Author Contributions

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Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author (Hao Xuerui) on reasonable request.

Ethics Statement

This research adheres to all applicable ethical standards, including but not limited to the welfare of experimental animals and informed consent for human studies.

Conflict of Interest Statement

The authors declare that there are no financial or personal conflicts of interest that could influence the interpretation of the results of this study.

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

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