

Quadrupole mode-based multipactor suppression in SSR cavities and its impact on beam dynamics

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Multipactor (MP) discharge is a critical limitation in superconducting radio-frequency (SRF) cavities, impacting the quality factor and cryogenic stability. In this article, we present a novel mitigation strategy to mitigate MP discharge by utilizing specific higher order quadrupole modes in single spoke resonator (SSR) cavities, designed for the MEHIPA-II linac. We demonstrate that the presence of a specific quadrupole mode leads to the effective suppression of MP in that SSR cavity and show that the quadrupole modes have minimal influence on the proton beam across the 40–200 MeV energy range. Analytical proofs based on field symmetry, supported by numerical simulations, confirm that the excitation of the quadrupole field results in zero net transverse kick and negligible emittance growth of the proton beam. This approach provides a flexible and alternative solution against persistent electron activity, overcoming a long-standing limitation to stable, high-gradient SRF operation.

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I. INTRODUCTION

Multipactor (MP) [1–3] is a phenomenon of resonant discharge encountered in many high-power rf devices and accelerator cavities, in which an avalanche of electron population occurs through secondary electron emission [4,5]. Multipacting discharge occurs when free electrons, energized by oscillating rf fields, impact the interior wall surface and generate secondary electrons. As the process begins to repeat in every cycle of the rf wave, the number of electrons increases exponentially with time. In this particular context, of special concern is the operation of the superconducting rf cavity, where the deposited microwave power is drained in the acceleration of the parasitic electron crowd, causing a sudden drop in the Q value. In addition, the electron transfers heat to the wall upon impact, leading to a higher cryogenic load. Due to these factors, a major part of the research efforts have leaned toward mitigation of the MP phenomenon.

Several methods for the mitigation of multipacting discharge, together with their respective application areas, have been discussed and reviewed in [3,6–16] and the

references therein. Very recently, an innovative approach was presented in Ref. [16] for the suppression of MP discharge in a superconducting spoke resonator (SSR) cavity, by utilizing higher order modes (HOMs). In that study, it was discussed that the excitation of some specific quadrupolar modes can potentially be an effective means to suppress MP in an SSR cavity. However, the physical rationale for prioritizing quadrupolar modes over dipolar modes was not entirely persuasive. There exists a better reason behind giving preference to a quadrupolar mode for the application discussed here. Moreover, the operational regimes in which this approach is intended to be applied, specifically whether the technique is applicable during active beam acceleration or limited to rf conditioning, were not clearly specified. In particular, its usefulness at the time of beam acceleration remained to be investigated. As noted in [16], the viability of employing quadrupole modes for multipacting suppression during beam operation depends critically on their influence on the proton beam. Without a thorough assessment of the potential impact of the excited HOMs on the proton beam, the utility of this method will remain speculative.

In this article, we address these gaps to establish HOM-based multipactor mitigation as a practical solution that can be applicable even during beam operation. We provide the physical basis for selecting a quadrupole mode for MP suppression and prove analytically and numerically that it does not create significant perturbation to the beam in the MEHIPA-II proton linac [17] where the beam bunches are

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accelerated from 40 to 200 MeV. This particular finding contributes significantly by extending the HOM-based approach for MP suppression to scenarios that include beam acceleration. The article is organized as follows: Section II explains the reasons for preferring a quadrupole mode over a dipole mode and demonstrates that multipacting discharge can be mitigated using a specific quadrupole mode in an SSR cavity. Section III presents a numerical investigation of the impact of this quadrupole mode on beam dynamics. Section IV discusses the potential applicability of this multipactor mitigation approach at the operating gradient in various operational linacs. Finally, the conclusion is drawn in Sec. V.

II. SUPPRESSION OF MP USING HOM

Among the various HOMs, four quadrupolar modes were identified as capable of suppressing the multipactor in the SSR cavity, namely the 9th, 12th, 15th, and 38th modes, with corresponding frequencies of 1.115, 1.221, 1.270, and 1.663 GHz, respectively [16]. The basic idea behind preferring quadrupolar modes over dipolar modes for multipacting suppression was to retain the possibility of employing this scheme even during beam operation. In the presence of a dipole mode, the particle beam would get transverse kick, leading to beam loss. In contrast, a quadrupole mode, or any other higher order multipole, produces no net transverse force on the beam centroid as a result of the symmetry of its transverse fields. This distinction follows directly from the Panofsky-Wenzel (PW) theorem [18]. Let us consider a charged particle with velocity v and charge q traveling through an rf cavity of length, say d , near and parallel to the axis. Panofsky-Wenzel theorem says that the transverse momentum change of the particle over the length d is given by

$$\Delta \vec{p}_\perp = \frac{jq}{\omega} \int_0^d \vec{\nabla}_\perp E_z dz. \quad (1)$$

The equation implies that the transverse impulse imparted to the particle is directly proportional to the transverse gradient of the longitudinal electric field of the rf cavity. For illustration, the functional form of the longitudinal electric field for the n -pole mode of a pill-box type cavity is

$$E_z = J_n(\chi_{np} r/R) \cos(n\theta), \quad (2)$$

where χ_{np} is the p th root of the Bessel function of order n , and R is the radius of the cavity. The Bessel function has the series expansion

$$J_n(x) = a_0 x^n + a_1 x^{n+2} + \dots \quad (3)$$

with $a_0, a_1, \dots$ being the expansion coefficients. Although the actual SSR cavity does not have pill-box geometry, the spatial behavior of the field near the axis is qualitatively

similar, making this example worth considering. For a dipole mode ($n = 1$), the resulting transverse impulse takes the form

$$\Delta \vec{p}_\perp \sim (a_0 + 3a_1 r^2) \cos \theta \hat{r} - (a_0 + a_1 r^2) \sin \theta \hat{\theta} \quad (4)$$

which remains nonzero even on the axis ($r = 0$). In contrast, for a quadrupole mode ($n = 2$), one obtains

$$\Delta \vec{p}_\perp \sim 2(a_0 r + 2a_1 r^3) \cos(2\theta) \hat{r} - 2(a_0 r + a_1 r^3) \sin(2\theta) \hat{\theta} \quad (5)$$

which vanishes at $r = 0$, i.e., on the axis. Very close to axis, the transverse impulse reduces to

$$\Delta \vec{p}_\perp \propto 2a_0(x\hat{x} - y\hat{y}), \quad (6)$$

implying that the beam is defocused in the x direction and focused in the y direction but experiences no net transverse impulsive force or displacement of its centroid. In the above analysis, higher order terms in the series expansion of $J_n(\chi_{np} r/R)$ have been neglected under the assumption $(r/R) \ll 1$, i.e., sufficiently close to the axis. All symbols appearing in the discussion carry their standard meanings, for the position variables and unit vectors in cylindrical and Cartesian coordinate systems.

The above argument holds specifically for TM modes or for a relativistic particle, in which case only the longitudinal electric field contributes to causing transverse deflection of the charged particle. A nonrelativistic particle, however, may still experience a transverse kick in the presence of a TE mode. While calculating the HOMs using the eigenmode solver, the x - z and y - z symmetry planes are treated as electric boundaries, which naturally support quadrupole modes but exclude TE dipole modes. A TE dipole mode possesses a finite transverse electric field on the axis, enabling it to impart a transverse deflection to the beam. By contrast, the electric field of a TE quadrupole mode always vanishes on axis. In quadrupole or higher order multipole modes, the transverse electric field reverses direction as one crosses the axis, making the axis a saddle point of the electric potential—exhibiting a maximum in one transverse direction and a minimum in the orthogonal direction. As a result, a TE quadrupole mode also cannot impart any net transverse deflection to a charged particle beam.

The preceding discussion clarifies why dipolar modes are unsuitable for the proposed application and motivates the preference for quadrupole or higher order multipole modes. Among the various quadrupole modes, only those whose electric and magnetic field maxima coincide with regions typically prone to MP within the cavity are suitable for the MP suppression. The rationale behind this stipulation is that to disrupt the motion of secondary electrons,

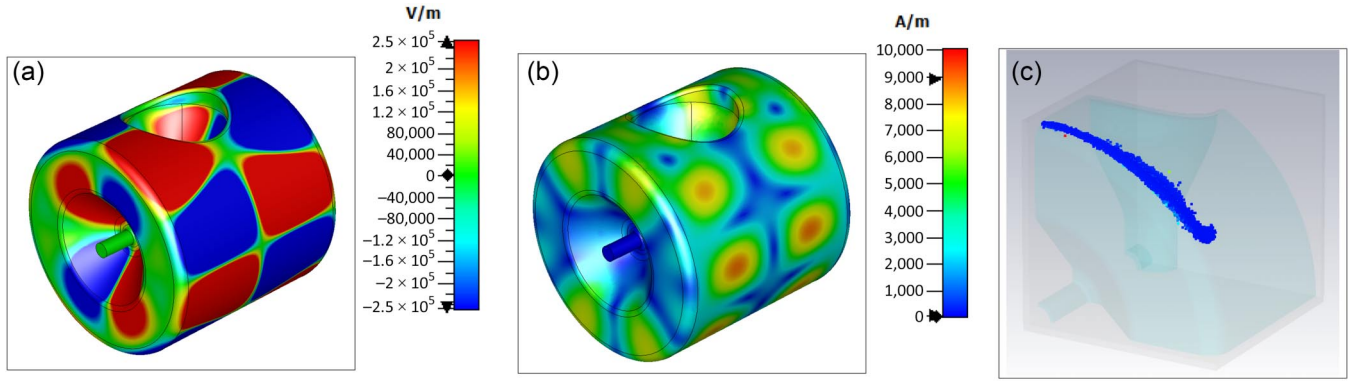


FIG. 1. (a) Electric and (b) magnetic field distribution of ninth quadrupole mode of the SSR-C cavity, and (c) accumulated secondary electrons of MP discharge at 11 MV/m accelerating gradient.

an electromagnetic field is required at the location where the avalanche is occurring.

The present work includes an investigation of MP discharge in an SSR cavity (categorized as SSR-C), which was designed during the design studies of MEHIPA accelerator [17]. The geometry serves as a representative model for our analysis. MP simulations were carried out at the operating gradient of 11 MV/m, and it has been shown that in the presence of a particular HOM (ninth quadrupole mode of the SSR-C cavity), MP growth can be suppressed. All simulations have been performed using CST Particle Studio (CST-PS) [19]. The electromagnetic field of the fundamental mode was calculated using CST Microwave Studio (CST MWS) eigen-mode solver, which was imported into CST Particle Studio for particle tracking. The simulation was executed with an SSR model of 300°C-baked niobium. To reduce computational load, a one-eighth symmetry model of the cavity was considered. In this approach, slabs of perfectly reflecting material were applied along the symmetry planes, ensuring that electrons striking these boundaries undergo elastic reflection, thereby mimicking the full cavity behavior. Secondary electron emission was modeled using the Furman probabilistic model [5], with parameters corresponding to 300°C-baked niobium. A Gaussian electron bunch with a kinetic energy of 300 eV and a temporal width of approximately 3 ns (comparable to the rf period of the fundamental mode) was used as the initial seed for the simulations. To ensure numerical accuracy, mesh convergence studies were performed by varying the mesh density, where MP growth rate [20] saturates with increasing the mesh resolution. An optimal mesh configuration was selected in each simulation case.

Figure 1 shows the electric and magnetic field distributions of the ninth quadrupole mode of the SSR-C cavity, along with the MP discharge site at the accelerating gradient of 11 MV/m. It is observed that the maxima of the electromagnetic field for this mode spatially coincide with the MP discharge location. This correspondence

provides the basis for selecting the ninth quadrupole mode as a suitable candidate for MP suppression. Figure 2 shows the evolution of the electron population in the SSR-C cavity at the operating accelerating gradient ($E_{\text{acc}} = 11$ MV/m) for different energy contents of the ninth quadrupolar mode. The results indicate that complete suppression of MP discharge is achieved when the ninth quadrupolar mode is excited with an energy content of 1 J at the operating gradient. In conjunction with the earlier demonstration that quadrupolar modes induce no net transverse kick to the beam bunches, these findings suggest that the use of quadrupole modes provides a promising pathway toward the mitigation of MP, a long-standing challenge in operation of superconducting accelerators.

III. EFFECT OF HOMs ON BEAM DYNAMICS

Although quadrupole modes do not impart a net transverse deflection to the beam, they can still induce adverse effects, such as beam quality degradation or an increase in beam size, that necessitate a detailed numerical simulation. In this study, the influence of ninth quadrupole modes is

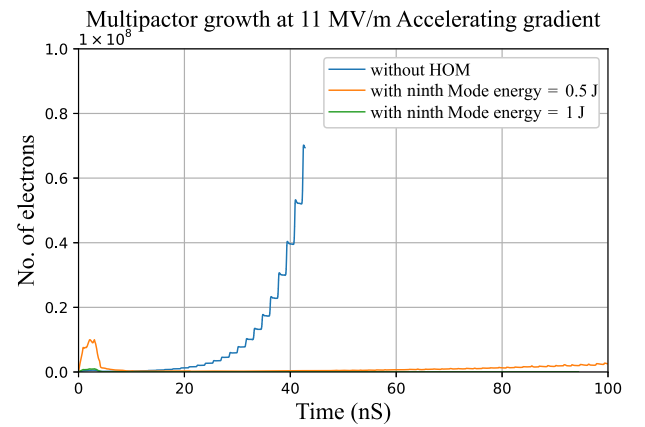


FIG. 2. Variation of number of electrons in SSR-C cavity with time at 11 MV/m accelerating gradient in the presence of ninth quadrupole mode.

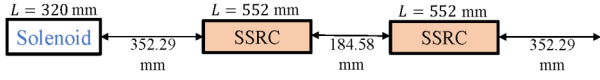


FIG. 3. Basic lattice of MEHIPA-II lattice.

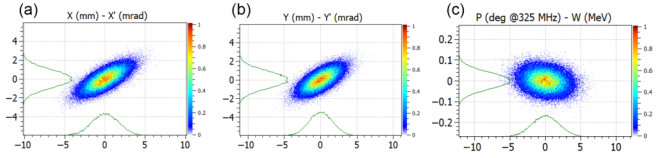
investigated in the MEHIPA-II lattice, originally designed in Ref. [17], using the particle-in-cell (PIC)-based beam dynamics code TraceWin [21] and PASUPAT [22,23], where a proton beam with beam current of 10 mA is accelerated from 40 to 200 MeV. TraceWin is a well-established and widely used tool for fast beam dynamic simulation offering broad range of functionalities, while PASUPAT is indigenously developed three-dimensional PIC code having fully electromagnetic as well as electrostatic solver. It has already been used for studying various electron emission phenomena with space charge in vacuum diode applications. In the present study, the space-charge field has been calculated employing its electrostatic solver, which uses the Gauss-Seidel-based multigrid method to solve Poisson equation. For this work, the code was upgraded and moving boundary (or moving window) algorithm was implemented to calculate the space-charge field only around the charged particle bunch under consideration, enabling beam dynamic simulation with space charge for a very long simulation domain possible in reasonable time period.

The basic lattice configuration, considered in the simulation, is shown in Fig. 3, which comprises a superconducting solenoid and two spoke cavities. Three such basic lattice units will be housed in a cryomodule, with a 400 mm drift space separating two consecutive cryomodules. The complete MEHIPA-II lattice consists of six cryomodules, as detailed in Ref. [17]. The initial Twiss parameters of the beam, listed in Table I, correspond to the matched ellipse parameters of the basic lattice, for 10 mA beam current. These Twiss parameters were adopted as the starting conditions for the present case study. The input beam distribution has been assumed to be Gaussian, as shown in Fig. 4. The output beam distribution is presented later, during comparison of simulation results under various scenarios.

Beam transport simulations were performed under excitation of multiple modes in the SSR-C cavity using both the

TABLE I. Twiss parameters of the input beam.

Twiss parameters (unit)	Value
α_x/α_y	$-1.0815/-0.9520$
β_x/β_y (mm/ π mrad)	2.682/2.5367
Emittance (ϵ_x/ϵ_y) (π mm mrad)	0.3
α_ϕ	0.203
β_ϕ (deg/ π MeV)	48.598
Longitudinal emittance (ϵ_ϕ) (π deg MeV)	0.0732

FIG. 4. Input beam distributions along x , y , and z planes.

TraceWin and PASUPAT codes. In TraceWin, the excitation of both the fundamental mode and HOMs was implemented through the “SUPERPOSE_MAP” command, which facilitates the application of field maps corresponding to two or more modes of distinct frequencies at the same location of the accelerator lattice under study. In case of PASUPAT, the field maps corresponding to the fundamental mode and the HOMs were imported and superposed. The required field maps were generated using the CST MWS eigenmode solver [24]. For completeness, a comparative study between the two codes was carried out, and the results are presented in Fig. 5, which shows the evolution of the beam envelope and emittance along the lattice. For brevity, only the horizontal (x) plane results are

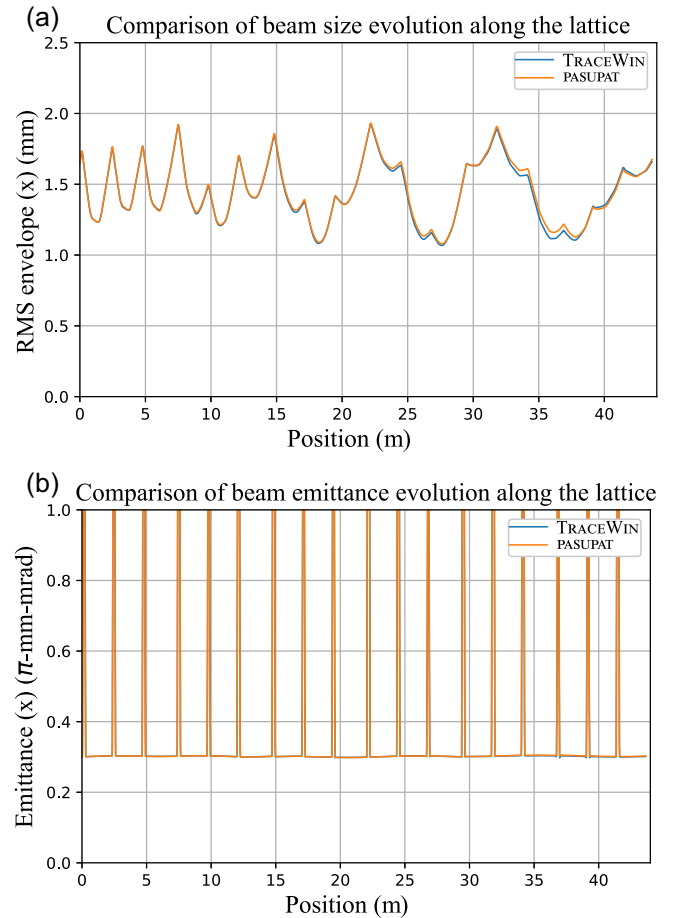
FIG. 5. Comparison of beam size (rms x_{envelope}) and emittance (normalized $x_{\text{emittance}}$) along the MEHIPA-II lattice for simulations using TraceWin and PASUPAT codes.

TABLE II. Comparison of the output beam Twiss parameters.

Twiss parameters (unit)	TraceWin	PASUPAT
α_x/α_y	-0.599/-0.790	-0.682/-0.888
β_x/β_y (mm/ π mrad)	6.292/7.813	6.386/8.106
Emittance (ϵ_x/ϵ_y) (π mm mrad)	0.301/0.315	0.302/0.311
α_ϕ	-0.267	-0.324
β_ϕ (deg/ π MeV)	8.937	10.135
Longitudinal emittance (ϵ_ϕ) (π deg MeV)	0.0807	0.0817

shown. The corresponding output Twiss parameters obtained from both codes are listed in Table II. The simulation results demonstrate excellent agreement between the two codes. However, to maintain uniformity and consistency in the analysis and presentation, only the results obtained using TraceWin are presented in the remainder of this paper.

The beam transport simulation has been conducted in the presence of the ninth quadrupole mode. In previous section, the excitation of ninth quadrupole mode with 1 J of energy content has shown to be sufficient for multipacting suppression at the operating gradient ($E_{\text{acc}} = 11$ MV/m) of the SSR-C cavity. In the present study, however, the influence of this mode on beam dynamics is examined for significantly larger, intentionally exaggerated energy contents of 10 J. Here, the exaggerated energy level is considered to investigate whether, in future practical scenarios requiring stronger excitation of a quadrupole mode, the resulting fields would have any adverse impact on the beam dynamics. In Table III, the Twiss parameters of the output beam are compared for beam dynamics simulations performed with

TABLE III. Comparison of the Twiss parameters of the output beam distributions for beam dynamics in the presence of the ninth mode at different energies.

Twiss parameters (unit)	Without HOM	Ninth mode (energy = 1 J)	Ninth mode (energy = 10 J)
α_x/α_y	-0.599/-0.790	-0.596/-0.791	-0.588/-0.791
β_x/β_y (mm/ π mrad)	6.292/7.813	6.279/7.828	6.249/7.861
Emittance (ϵ_x/ϵ_y) (π mm mrad)	0.301/0.315	0.301/0.315	0.301/0.316
α_ϕ	-0.267	-0.267	-0.268
β_ϕ (deg/ π MeV)	8.937	8.932	8.919
Longitudinal emittance (ϵ_ϕ) (π deg MeV)	0.0807	0.0807	0.0807

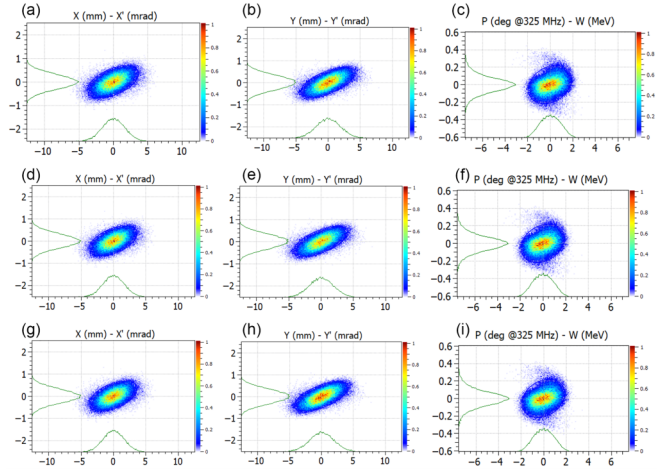


FIG. 6. Output beam distributions along x , y , and z planes. The first row presents the results without any HOM excitation. The second and third rows show the output distributions when the ninth quadrupole mode is excited with energy contents of 1 and 10 J, respectively.

excitation of the ninth quadrupole mode at different energy levels. Figure 6 presents the corresponding output beam distributions for these same scenarios. And in Fig. 7, the evolution of the rms beam size and the rms emittance (in both the transverse and longitudinal directions) is shown, for comparison purposes between the cases of no HOMs and the presence of the ninth quadrupole mode with different energy contents. These results indicate that the ninth mode has a minimal influence on the beam dynamics, even at unrealistically high excitation energy, suggesting its suitability for MP suppression at the operating gradient of the SSR-C cavity during beam acceleration.

The influence of the ninth mode was further assessed for an off-axis beam. The input beam was displaced deliberately by 3.5355 mm in both transverse directions, giving a total offset of 5 mm. The simulations were then carried out for two cases: without any HOM excitation and with the ninth quadrupole mode excited to 10 J energy level. Table IV compares the resulting output Twiss parameters, revealing only marginal differences between the two cases. Figure 8 illustrates the corresponding output beam distributions. The evolution of beam size, emittance, and centroid position along the lattice, presented in Fig. 9, confirms that the ninth quadrupole mode does not introduce any significant perturbations, even for a transversely displaced beam.

To further clarify the innocuous nature of the excited HOM to accelerated beam, a comparison study is presented here. The effect of the ninth quadrupole mode on the energy change of a unit test charge at a finite radial offset from the axis while traversing the cavity is compared with that of the space-charge forces of the bunch itself. For quadrupole modes, the electric field strength near the

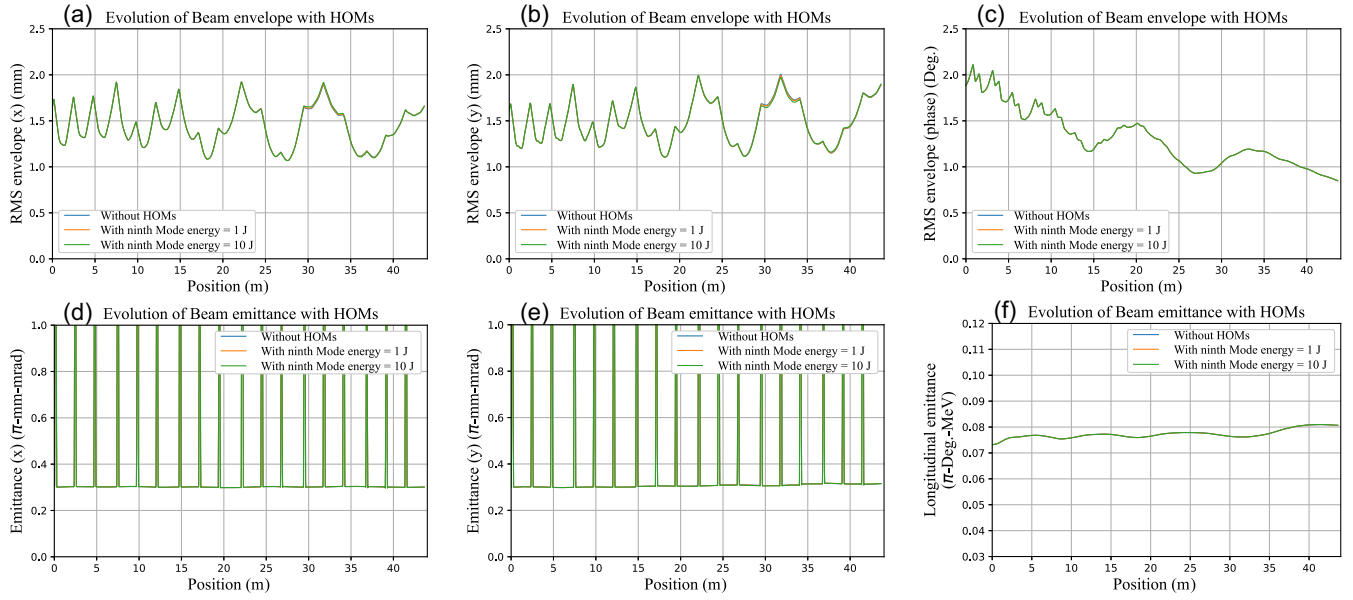


FIG. 7. Comparison of beam envelope and emittance evolution along the MEHIPA-II lattice for two cases: in the absence of HOM excitation and in the presence of the ninth quadrupole mode with different stored energy levels. Figures 7(a)–7(c) show the evolution of the rms beam size in the horizontal, vertical, and phase planes, respectively, while Figs. 7(d)–7(f) present the corresponding normalized transverse emittances and the (unnormalized) longitudinal emittance.

cavity axis is inherently weak due to its quadratic radial dependence, scaling as $\sim(r/R)^2$, where r is the radial distance from the axis and R is the cavity radius. The ninth mode under consideration is a TE quadrupolar mode, for which the transverse electric field at a radial offset of 5 mm from the axis is of the order of ~ 16 kV/m, for 1 J energy content. In addition, the time-varying quadrupole fields associated with an HOM undergo multiple sign reversals during the transit of a bunch through the cavity, leading to a negligibly small net transverse effect. The time-averaged transverse voltage imparted by the ninth quadrupole mode for a beam with a relativistic factor $\beta = 0.5$ is estimated to be only about

147 V, over a cavity length of 550 mm (calculated using CST MWS eigenmode solver). In contrast, the transverse electric field at a radial offset of 5 mm from the axis arising from the space charge of a 10 mA, 325 MHz proton beam is approximately 11 kV/m, assuming the beam bunch as a spherically symmetric Gaussian charge distribution of standard deviation 1.5 mm, for a rough estimate. The integrated transverse voltage experienced by a particle due to space-charge forces while traversing a cavity of length 550 mm is nearly 6.05 kV. This comparison reflects that the influence of the quadrupolar HOM is even negligible when compared to the self space-charge force of the beam.

TABLE IV. Comparison of the output beam Twiss parameters for an initial beam offset of 5 mm.

Twiss parameters (unit)	Without HOM	Ninth mode (energy = 10 J)
α_x/α_y	-0.575/-0.747	-0.560 /-0.742
β_x/β_y (mm/ π mrad)	6.149/7.779	6.107/7.801
Emittance (ϵ_x/ϵ_y) (π mm mrad)	0.301/0.321	0.301/0.320
α_ϕ	-0.216	-0.216
β_ϕ (deg/ π MeV)	8.743	8.718
Longitudinal emittance (ϵ_ϕ) (π deg MeV)	0.0836	0.0837

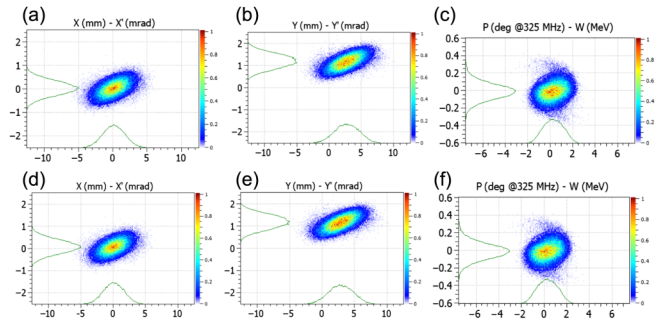


FIG. 8. Output beam distributions for an initial beam offset of 5 mm. The upper row shows the case without any HOM excitation, while the lower row corresponds to the results obtained with excitation of the ninth mode at an energy content of 10 J.

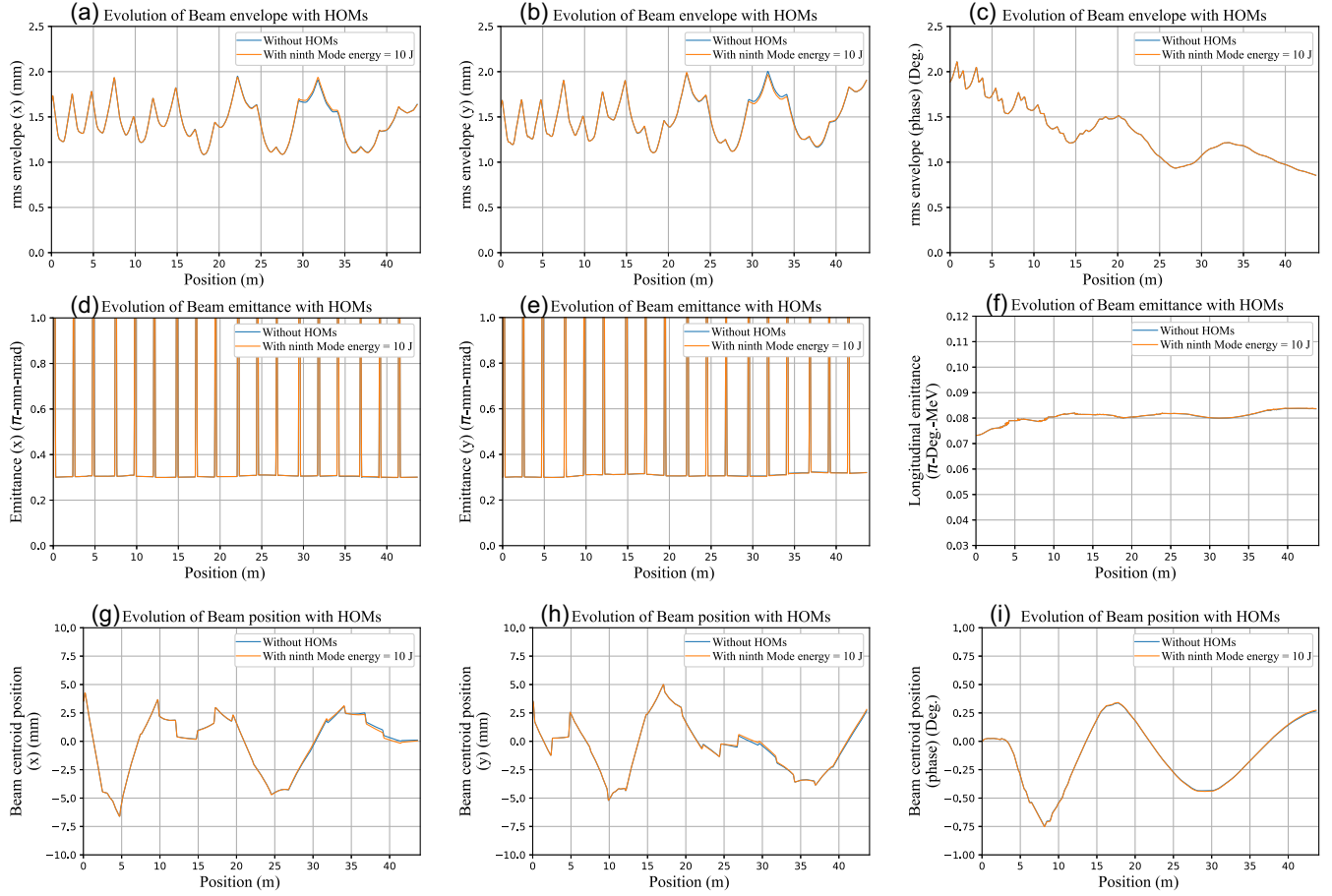


FIG. 9. Comparison of beam envelope, emittance, and beam position evolution along the accelerator lattice for a radially offset beam, under two conditions: in the absence of HOM excitation and in the presence of the ninth quadrupole mode with a stored energy of 10 J. Figures 9(a)–9(c) show the evolution of the rms beam size in the horizontal, vertical, and phase planes, respectively, while Figs. 9(d)–9(f) present the corresponding normalized transverse emittances and the (unnormalized) longitudinal emittance. The evolution of the beam centroid in the three directions is shown in Figs. 9(g)–9(i), respectively.

IV. DISCUSSION

In this work, a particular quadrupole mode (ninth quadrupole mode of the SSR-C cavity) has been demonstrated to mitigate multipacting discharge at the operating gradient of the cavity. In addition, it is shown, through both qualitative arguments and beam dynamics simulations, that quadrupole modes have a negligible impact on the proton beam in the MEHIPA-II lattice over the energy range of 40 to 200 MeV. The result allows for the use of quadrupole modes to mitigate multipacting in spoke cavities during beam acceleration. At the operating gradient, excitation of an auxiliary quadrupole mode will allow the machine to run without interruption.

In addition to that, the proposed method can also be beneficial in suppressing multipactor discharge at the time of rf conditioning, provided suitable quadrupole modes are found at the intermediate accelerating gradients of the cavity under operation. The controlled excitation of preselected HOMs can be employed to overcome

multipacting barriers encountered at various accelerating gradients as the superconducting cavity field is ramped up to its nominal operating value, thereby significantly reducing the duration and complexity of the conditioning process.

Although conditioning suppresses multipacting in pulsed systems such as SNS [25], it often fails in long-term cw scenarios, leading to thermal instability, quenches, and trips from recurring electron avalanches. The operational experience reported in Ref. [25] demonstrates that the electron loading associated with multipacting and field emission occurs close to the nominal accelerating gradient and contributes to radiation onset, cavity trips, and thermal instability, particularly under high duty-factor operation. Although SNS is a pulsed machine, the study emphasizes that sustained electron activity at operating fields can produce localized heating and limit stable gradient margins, an issue expected to be more severe in continuous-wave (cw) SRF accelerators. The same

reference further notes that “the multipacting at higher gradients in contrast cannot be always completely conditioned out and even is the main limiting factor for some cavities in the SCL.” In addition, very stable multipacting has been observed in certain cavities even after 10 years of operation, which indicates that sometimes the stable secondary emission yield is the main reason of multipacting rather than the adsorbed gasses. Similar persistence of cavity-related electron-induced phenomena after conditioning has been reported in other SRF systems, notably in LCLS-II cryomodels, where multipacting bands in the cavities overlap with the nominal operating gradient and can reappear during cryomodel testing and operation [26,27]. References [28–30] reported the occurrence of field-emission-induced multipacting in which case, even though the secondary emission yield is not high enough for self-sustained multipactor, but continuous capturing of the field-emitted electrons compensates the lack of secondary electrons and leads to absorption of rf power and Q -drop. Although these observations of persistent multipacting at operating gradients do not specifically pertain to single spoke resonator (SSR) cavities, they collectively highlight the need for active mitigation strategies capable of suppressing multipacting at or near nominal operating fields, thereby motivating the HOM-based mitigation approach investigated in this work.

The experimental feasibility of the present scheme of MP mitigation hinges upon several practical aspects. First, deliberate excitation of HOMs introduces additional rf power dissipation in the cavity, which must be adequately handled by the cryogenic system to maintain the cavity strictly in the superconducting state. For the fundamental operating mode at an accelerating gradient of 11 MV/m, the power dissipated in the cavity is approximately 9.9 W (considering a surface resistance R_s of 14.4 n Ω at 325 MHz as reported in Ref. [31]). In comparison, the presence of the ninth mode with an energy content of 1 J results in an additional power dissipation of about 0.318 W, contributing an extra thermal load. Although this additional load is relatively small compared with the power dissipated by the operating mode, it must nevertheless be carefully accounted for in the cryogenic design consideration. Second, the effective excitation of the selected HOMs necessitates the fabrication and installation of a dedicated wideband HOM coupler to couple the preselected quadrupole modes to the cavity. The HOM coupler also serves as a thermal bridge between ambient temperature (~ 300 K) and the cryogenic environment (2 K). The resulting temperature gradient, together with rf losses in the coupler, contributes additional thermal load, which must be managed using appropriate thermal intercepts in the cryogenic system. A comprehensive design study of an HOM coupler, including an analysis of the static and dynamic heat loads associated with its integration, has been presented in Ref. [32] and is not

repeated here for brevity. The thermal simulation in that study showed that the static heat load on the 2 K cryogenic system is approximately 0.236 W. However, the dissipated heat due to the propagation of the HOMs is entirely borne by 5 and 50 K thermal intercepts, rendering the dynamic thermal load on the 2 K system practically negligible. In addition to those, another important prerequisite is a suitable power amplifier (PA) and a complete low-level rf control system. Depending on the frequency of the selected HOMs, multiple signal sources, power amplifiers, circulators, and matched rf loads spanning distinct frequency bands must be available for the successful implementation of this scheme [33]. For the PAs, the specification of the required frequency band and power level is of paramount importance. Although Ref. [32] indicates that maintaining 1 J of stored energy in the cavity for the ninth quadrupole mode requires an input power of less than 1 kW, we conservatively assume that the required power may reach to a few kilowatts in order to retain flexibility for future operating scenarios. In addition, sufficient bandwidth is necessary, as the frequency of a given HOM may vary during operation due to several factors, such as the tuning of the fundamental mode. Recent advances in GaN technology [34] have made the wideband and high-power rf amplifier more accessible. Nonetheless, a comprehensive design considerations of these rf engineering aspects require dedicated investigations and constitute a separate study. With these technological advancements, our present research introduces a novel framework for mitigating MP phenomena in superconducting cavities, thereby enabling uninterrupted operation of high-energy accelerator.

V. CONCLUSION

In this article, a novel method for mitigating MP discharge in an SSR cavity is proposed using higher order quadrupole modes, and it is demonstrated that these modes have minimal impact on the proton beam over the 40–200 MeV energy range. Specifically, excitation of the ninth quadrupole mode of the SSR-C cavity is shown to effectively disrupt resonant electron trajectories at the operating gradient without compromising beam quality. The proposed approach makes use of the inherent symmetry of the quadrupole field. Using the Panofsky-Wenzel theorem, it is analytically shown that the net transverse kick imparted to the beam vanishes. These analytical predictions are further corroborated through comprehensive beam dynamics simulations, which confirm that the quadrupolar mode has a negligible impact on the proton beam. The ninth quadrupole mode of the SSR-C cavity is found to have minimal influence on both longitudinal and transverse emittance, even at high stored HOM energies of up to 10 J, for a 10 mA proton beam accelerated from 40 to 200 MeV. The findings presented in this work highlight the potential of the proposed approach in enhancing long-term

operational stability of the superconducting linac and accelerator systems. The technical challenges in conjunction with the excitation of an auxiliary HOM have also been addressed.

Beyond the specific case studied here, the proposed strategy offers a general framework for multipacting control in superconducting spoke cavities. Since the effectiveness of the method relies on the spatial overlap between the field maxima of the selected higher order mode and the multipacting-prone regions, the approach can be systematically extended to other cavity geometries by appropriate identification and excitation of suitable quadrupolar or higher order multipole modes.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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- [1] J. R. M. Vaughan, Multipactor, *IEEE Trans. Electron Devices* **35**, 1172 (1988).
 - [2] R. A. Kishek, Y. Y. Lau, L. K. Ang, A. Valfells, and R. M. Gilgenbach, Multipactor discharge on metals and dielectrics: Historical review and recent theories, *Phys. Plasmas* **5**, 2120 (1998).
 - [3] A. Iqbal, D.-Q. Wen, J. Verboncoeur, and P. Zhang, Recent advances in multipactor physics and mitigation, *High Voltage* **8**, 1095 (2023).
 - [4] J. R. M. Vaughan, A new formula for secondary emission yield, *IEEE Trans. Electron Devices* **36**, 1963 (1989).
 - [5] M. A. Furman and M. T. F. Pivi, Probabilistic model for the simulation of secondary electron emission, *Phys. Rev. ST Accel. Beams* **5**, 124404 (2002).
 - [6] E. T. Tulu, U. van Rienen, and A. Arnold, Systematic study of multipactor suppression techniques for a superconducting rf gun, *Phys. Rev. Accel. Beams* **21**, 113402 (2018).
 - [7] L. Wang, T. O. Raubenheimer, and G. Stupakov, Suppression of secondary emission in a magnetic field using triangular and rectangular surfaces, *Nucl. Instrum. Methods Phys. Res., Sect. A* **571**, 588 (2007).
 - [8] M. Pivi, F. K. King, R. E. Kirby, T. O. Raubenheimer, G. Stupakov, and F. Le Pimpec, Sharp reduction of the secondary electron emission yield from grooved surfaces, *J. Appl. Phys.* **104**, 104904 (2008).
 - [9] G. Romanov, P. Berrutti, and T. Khabiboulline, Simulation of multipacting in SC low beta cavities at FNAL, Fermi National Accelerator Lab. (FNAL), Technical Report No. FERMILAB-CONF-15-152-TD, 2015.
 - [10] P. Berrutti, I. Gonin, T. N. Khabiboulline, M. Parise, D. Passarelli, G. Romanov, F. Rui, A. Sukhanov, and V. Yakovlev, New design of SSR2 spoke cavity for PIP II SRF linac, Fermi National Accelerator Lab. (FNAL), Technical Report No. FERMILAB-CONF-19-281-TD, 2019.
 - [11] R. Prakash, A. R. Jana, and V. Kumar, Multipacting studies in elliptic SRF cavities, *Nucl. Instrum. Methods Phys. Res., Sect. A* **867**, 128 (2017).
 - [12] R. L. Geng, H. Padamsee, S. Belomestnykh, P. Goudket, D. M. Dykes, and R. G. Carter, Suppression of multipacting in rectangular coupler waveguides, *Nucl. Instrum. Methods Phys. Res., Sect. A* **508**, 227 (2003).
 - [13] D. González-Iglesias, A. M. Pérez, S. Anza, J. V. Cardona, B. Gimeno, V. E. Boria, D. Raboso, C. Vicente, J. Gil, and F. Caspers, Multipactor mitigation in coaxial lines by means of permanent magnets, *IEEE Trans. Electron Devices* **61**, 4224 (2014).
 - [14] C. Chang, G. Z. Liu, C. X. Tang, C. H. Chen, H. Shao, and W. H. Huang, Suppression of high-power microwave dielectric multipactor by resonant magnetic field, *Appl. Phys. Lett.* **96**, 111502 (2010).
 - [15] Y. Kalboussi, S. Dadouch, B. Delatte, F. Miserque, D. Dragoe, F. Eozenou, M. Baudrier, S. Tusseau-Nenez, Y. Zheng, and L. Maurice, Multipacting mitigation by atomic layer deposition: The case study of titanium nitride, *J. Appl. Phys.* **136**, 085301 (2024).
 - [16] A. K. Ghosh and V. L. S. R. Sista, Suppression of multipacting growth in a superconducting spoke resonator by the use of higher order modes, *J. Instrum.* **19**, P03005 (2024).
 - [17] A. Pathak, S. Roy, S. V. L. S. Rao, and S. Krishnagopal, Design study for medium energy high intensity proton accelerator, *Phys. Rev. Accel. Beams* **23**, 090101 (2020).
 - [18] T. P. Wangler, *RF Linear Accelerators* (John Wiley & Sons, New York, 2008).
 - [19] CST Particle Studio module, CST Studio Suite, Dassault Systèmes Deutschland GmbH, Darmstadt, Germany, <https://www.3ds.com/products/simulia/cst-studio-suite>.
 - [20] H. Wang, D. Liu, L. Liu, M. Xie, and L. Meng, Effects of rf magnetic field on upstream dielectric multipactor, *Plasma Sources Sci. Technol.* **27**, 125006 (2018).
 - [21] D. Uriot and N. Pichoff, TraceWin code, CEA/DSM/IRFU/SACM, Saclay, France (2014), <https://www.cea.fr>.
 - [22] G. Singh, Modeling space charge affected electron emission from the curved surface using particle-in-cell technique, Ph.D. thesis, Homi Bhabha National Institute, Mumbai, India, 2023.
 - [23] G. Singh, R. Kumar, and D. Biswas, Enhanced space charge limited current for curved electron emitters, *Phys. Plasmas* **27**, 103107 (2020).
 - [24] CST Microwave Studio module, CST Studio Suite, Dassault Systèmes Deutschland GmbH, Darmstadt, Germany, <https://www.3ds.com/products/simulia/cst-studio-suite>.
 - [25] S.-H. Kim, R. Afanador, D. L. Barnhart, M. Crofford, B. D. Degraff, M. Doleans, J. Galambos, S. W. Gold, M. P. Howell, and J. Mammoser, Overview of ten-year operation of the superconducting linear accelerator at the spallation neutron source, *Nucl. Instrum. Methods Phys. Res., Sect. A* **852**, 20 (2017).
 - [26] A. Cravatta, T. Arkan, D. Bafia, J. Kaluzny, S. Posen, J. Vennekate, M. Drury, S. Aderhold, M. Checchin, and

- D. Gonnella, Multipacting processing in cryomodules for LCLS-II and LCLS-II-HE, [arXiv:2306.17274](https://arxiv.org/abs/2306.17274).
- [27] S. Posen *et al.*, High gradient performance and quench behavior of a verification cryomodule for a high energy continuous wave linear accelerator, *Phys. Rev. Accel. Beams* **25**, 042001 (2022).
- [28] E. Donoghue, G. Wu, J. Mammoser, R. Rimmer, M. Stirbet, L. Phillips, and H. Wang, Studies of electron activities in SNS-Type superconducting RF cavities, in *Proceedings of the 12th International Workshop on RF Superconductivity, SRF'05, Cornell University, Ithaca, NY (JACoW, Geneva, Switzerland, 2005)*, pp. 402–405.
- [29] D. B. Caballero, W. Wuensch, K. Szypula, N. Lasheras, B. Gimeno, and A. Golfe, Combined field emission and multipactor simulation in high gradient rf accelerating structures, in *Proceedings of the 10th International Particle Accelerator Conference (IPAC'19)* (2019), p. 2940.
- [30] J. Brown, A. Sukhanov, D. Passarelli, G. Romanov, and T. Xu, Simulations of field emitters and multipacting in PIP-II single spoke resonator type-2, Fermi National Accelerator Laboratory (FNAL), Technical Report No. FERMILAB-CONF-24-0965-TD, 2024.
- [31] M. Ball, A. Burov, B. Chase, A. Chakravarty, A. Chen, S. Dixon, J. Edelen, A. Grassellino, D. Johnson, and S. Holmes, The PIP-II conceptual design report, Fermi National Accelerator Lab. (FNAL), Technical Report no. FERMILAB-DESIGN-2017-01 and FERMILAB-TM-2649-AD-APC, 2017.
- [32] A. K. Ghosh, M. Jose, V. L. S. R. Sista, and R. Kumar, Design of a higher order mode (HOM) coupler for suppression of multipactor in a 325 MHz SSR cavity, *J. Instrum.* **20**, P07041 (2025).
- [33] R. Bailey *et al.*, CAS—CERN accelerator school: Rf for accelerators, Technical Report No. CERN-2011-007, CERN, Ebeltoft, Denmark, 2010, p. 125.
- [34] K. Benson, GaN breaks barriers—RF power amplifiers go wide and high, *Analog Dialogue* **51** (2017), <https://www.analog.com/en/resources/analog-dialogue/articles/rf-power-amplifiers-go-wide-and-high.html>.