DESIGN AND TEST OF AN X-BAND CAVITY FOR SHORT-PULSE RF BREAKDOWN STUDIES

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Abstract

High-gradient operation of normal-conducting radiofrequency (RF) cavities is fundamentally limited by RF breakdown, a phenomenon driven by processes including field emission, surface heating, multipacting, and plasma formation. Recent studies have indicated that operating X-band RF cavities in a short-pulse regime, with RF pulses only a few nanoseconds long, can modify the onset and dynamics of RF breakdown. In particular, short pulses can limit multipactor-driven electron growth and reduce field-emission-induced Joule heating on cavity surfaces. However, systematic experimental investigations of these effects remain limited. We present the design of a dedicated experiment using a single-cell high-gradient X-band cavity to be tested at the Argonne Wakefield Accelerator (AWA) for studies of RF breakdown under short-pulse operation. The experiment will employ short, adjustable RF pulses in the few-nanosecond range. We describe the cavity design optimized for short-pulse operation, the planned operating parameter space, and the diagnostics for time-resolved dark current and RF measurements, with the goal of revealing breakdown behavior in the short-pulse regime.

INTRODUCTION

The maximum achievable accelerating gradient in normal-conducting radiofrequency (RF) structures is fundamentally limited by RF breakdown, which remains a critical constraint in the development of compact accelerators. Breakdown processes are governed by a combination of field emission, multipacting, surface heating, and plasma formation, among other phenomena. Their onset depends on the complex interplay of multiple factors, including local field conditions, surface materials, and structure geometry [1, 2].

Recent experiments at the Argonne Wakefield Accelerator (AWA) have demonstrated that operating X-band cavities with nanosecond-scale RF pulses can significantly modify breakdown behavior, enabling accelerating gradients approaching the sub-GV/m regime [3–6]. At AWA, these short high-power RF pulses are produced using an X-band power-extraction system driven by a high-charge multi-bunch train [5]. In this regime, the RF pulse duration becomes comparable to or shorter than the characteristic development time of breakdown-related processes, potentially suppressing electron multiplication and limiting surface heating. Recent analytical and numerical studies have further highlighted the importance of dark current and multipacting dynamics in short-pulse high-gradient RF structures [4, 7–9]. Understanding how the breakdown-related processes evolve in the short-pulse regime is therefore important for the development of future high-gradient normal-conducting accelerators.

While these results are promising, systematic experimental studies of RF breakdown in the short-pulse regime remain limited. In particular, fabrication and surface continuity may also influence dark current emission and breakdown onset. Here, we present the design and planned experimental study of a single-cell X-band cavity at 11.7 GHz, fabricated in two configurations: a mechanically clamped structure and a brazed structure. Both configurations share the same electromagnetic design. This enables a detail study of RF performance, dark current generation, and breakdown response under short-pulse excitation.

CAVITY DESIGN

A single-cell cavity operating at 11.7 GHz has been designed for studies of RF breakdown and dark current in the short-pulse regime at AWA. The structure employs a symmetric re-entrant geometry optimized for high-gradient operation under nanosecond-scale RF excitation. The cavity geometry is shown in Fig. 1(a), while Fig. 2 summarizes the

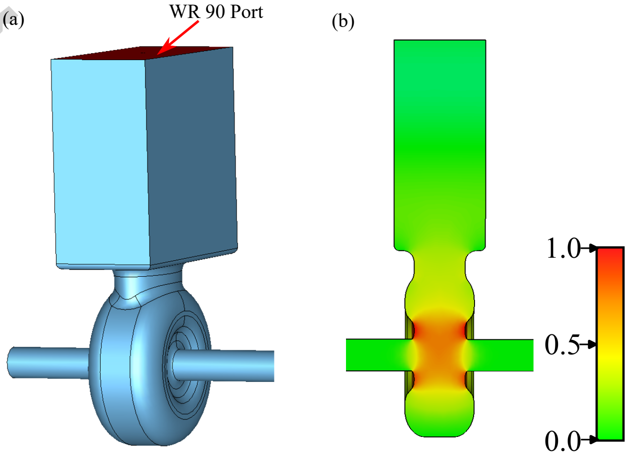

Figure 1: Geometry of the single-cell X-band cavity operating at 11.7 GHz. (a) Vacuum model of the cavity with the WR90 waveguide coupler. (b) Normalized E_z field distribution on the cavity midplane.

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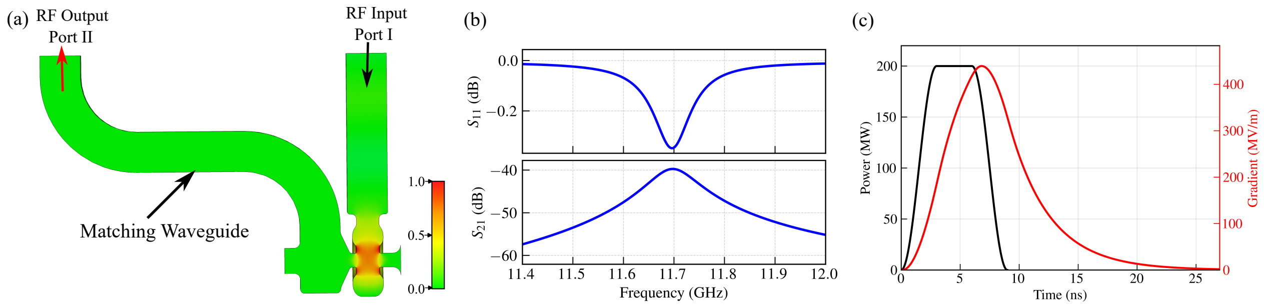

Figure 2: Single-cell X-band cavity design and its short-pulse RF response. (a) Normalized E_z field contour plot on the cavity midplane. (b) Simulated S_{11} and S_{21} responses of the cavity. (c) Time-domain evolution of the accelerating gradient (red) and the input RF power (black) for short-pulse excitation with a 9 ns pulse, corresponding to an effective full width at half maximum of about 6 ns.

electromagnetic design of the complete structure, including the simulated scattering parameters and the time-domain evolution of the accelerating gradient under short-pulse excitation.

The cavity geometry was optimized using the CST Microwave Studio with an emphasis on maximizing the transient accelerating gradient while controlling the peak surface electric and magnetic fields, since both are closely connected to breakdown initiation and surface stress [1, 2]. The normalized E_z field distribution of the operating mode on the cavity midplane is shown in Fig. 1(b). The corresponding normalized E_z field contour plot is shown in Fig. 2(a), while the simulated S_{11} and S_{21} responses in Fig. 2(b) confirm operation near the target frequency of 11.7 GHz and verify the weak coupling of the diagnostic waveguide.

The optimized RF parameters include a beam aperture radius of 1.76 mm, a loaded quality factor of approximately 130, and a cavity fill time of 6.86 ns, making the structure well matched to few-nanosecond RF pulses. The shunt impedance is 148 MΩ/m, with field ratios $E_p/E_0T = 1.65$ and $H_pZ_0/E_0T = 1.25$. Figure 2(c) shows the time-domain evolution of the accelerating gradient under short-pulse excitation, demonstrating that the cavity can be driven effectively within the pulse-length range relevant to the planned high-power experiment.

Two cavities sharing the same electromagnetic design have been fabricated for the experimental campaign. In one configuration, the cavity halves are mechanically joined to form a clamped structure, introducing a physical interface at the midplane. In the other, the two halves are brazed together to form a monolithic structure with improved electrical and thermal continuity. Together, these structures support the planned short-pulse studies of RF performance, dark current generation, and breakdown behavior. A weakly coupled diagnostic waveguide is incorporated into the design, with a transmission coefficient of approximately $S_{21} = -40$ dB, enabling real-time monitoring of cavity behavior without significantly perturbing the RF fields.

EXPERIMENTAL SETUP AND DIAGNOSTICS

The experimental study will be carried out at AWA using nanosecond-long RF pulses generated by the X-band power-extraction system developed for high-field short-pulse operation [3, 5]. Figure 3 shows the clamped cavity configuration used for the initial installation and testing, while Fig. 4 shows the planned vacuum assembly together with the associated diagnostics.

Figure 4 shows the test-chamber setup, which includes the cavity under test together with RF and dark-current diagnostics. Directional couplers DC1 and DC2 are used to monitor the RF signals at the input and output sides of the system, providing time-resolved measurements of the incident, reflected, and transmitted power. An RF probe is incorporated to monitor the leakage field during the pulse. A Faraday cup positioned downstream of the cavity is used to measure emitted dark current, providing direct information on field emission and possible electron multipacting.

This diagnostic layout is designed to correlate RF and dark-current measurements during high-gradient operation. Earlier studies have shown that time-resolved RF and dark-current signals are key observables for understanding break-

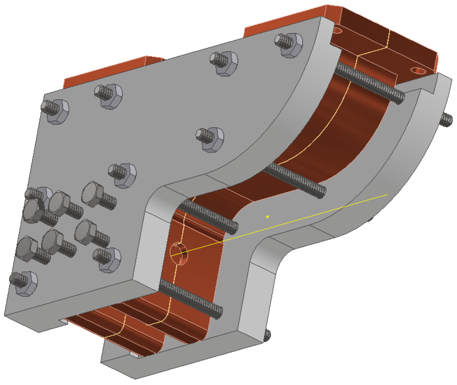

Figure 3: 3D CAD model of the clamped single-cell X-band cavity configuration used for the initial short-pulse breakdown studies. The figure shows the assembled test structure and its mechanical arrangement prior to integration into the full experimental setup.

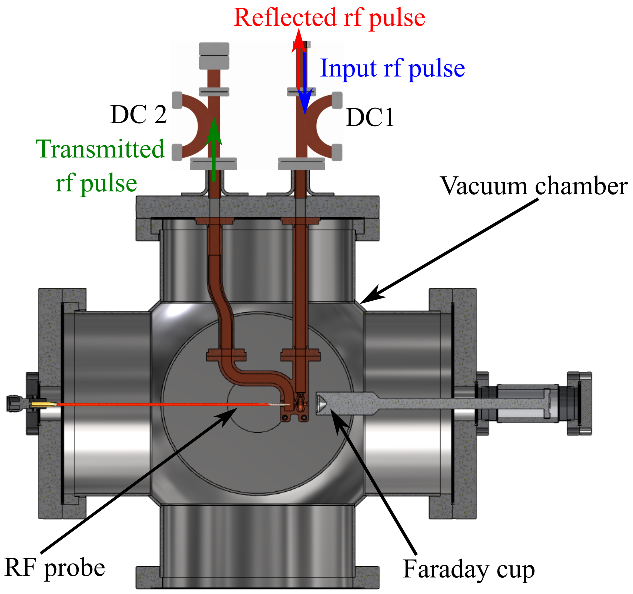

Figure 4: Experimental setup for short-pulse RF breakdown studies in the single-cell X-band cavity. The 3D CAD model shows the vacuum assembly of the cavity together with the main diagnostics, including the directional couplers (DC1 and DC2), the RF probe, and the downstream Faraday cup for dark-current measurement.

down behavior in high-gradient RF structures [4, 8, 10]. In the present experiment, these measurements will be used to track the temporal evolution of the cavity field and emitted charge under short-pulse excitation, and to study how these quantities change as a function of operating conditions.

LOW-POWER RF VALIDATION VIA ADDITIVE MANUFACTURING

To obtain an initial experimental validation of the RF design, we fabricated a structure prototype using additive manufacturing. preliminary low-power measurements were performed on a 3D-printed prototype having the same cavity geometry as the present cavity. The prototype, shown in Fig. 5(a), was fabricated by direct metal laser sintering (DMLS) using AlSi10Mg aluminum alloy.

The measured S_{11} and S_{21} responses are shown in Fig. 5(b) and Fig. 5(c), respectively. In comparison with the simulated response presented earlier in Fig. 2(b), the measurements show the expected overall RF behavior of the structure. The small shift in resonance frequency and the difference in S-parameter magnitude are attributed primarily to the lower electrical conductivity of AlSi10Mg and to the rougher surface finish associated with the 3D-printing process.

CONCLUSION AND OUTLOOK

A single-cell X-band cavity operating at 11.7 GHz has been designed for systematic studies of RF breakdown and dark current under nanosecond-scale short-pulse excitation. The electromagnetic design, simulated RF response, and preliminary low-power microwave measurement are presented, along with the experimental setup.

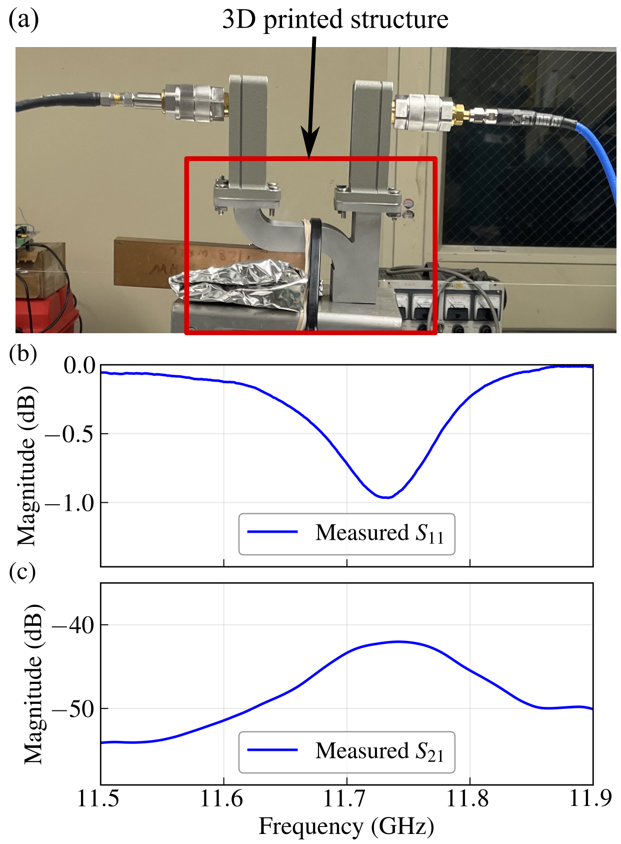

Figure 5: Preliminary low-power microwave measurement results for a 3D-printed prototype with the same target cavity geometry as the design. (a) 3D-printed cavity prototype (b) Measured S_{11} response. (c) Measured S_{21} response.

The planned configuration combines time-resolved RF diagnostics with dark-current measurements, enabling the correlation of reflected and transmitted RF signals, RF-probe response, and Faraday-cup signals during high-gradient operation. These studies aim to provide critical experimental data on breakdown scaling laws and electron multiplication processes, ultimately informing the design of next-generation, high-gradient compact accelerators.

ACKNOWLEDGMENTS

This research was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award DE-SC0021928.

REFERENCES

[1] A. Grudiev, S. Calatroni, and W. Wuensch, “New local field quantity describing the high gradient limit of accelerating structures”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 12, p. 102001, 2009. doi:10.1103/PhysRevSTAB.12.102001

[2] E. I. Simakov, V. A. Dolgashev, and S. G. Tantawi, “Advances in high gradient normal conducting accelerator structures”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 907, pp. 221–230, 2018. doi:10.1016/j.nima.2018.02.085

[3] W. H. Tan *et al.*, “Demonstration of sub-GV/m accelerating field in a photoemission electron gun powered by nanosecond X-band radio-frequency pulses”, *Phys. Rev. Accel. Beams*, vol. 25, p. 083402, 2022. doi:10.1103/PhysRevAccelBeams.25.083402

[4] D. Merenich *et al.*, “Breakdown insensitive acceleration regime in a metamaterial accelerating structure”, *Phys. Rev. Accel. Beams*, vol. 27, p. 041301, 2024. doi:10.1103/PhysRevAccelBeams.27.041301

[5] M. Peng *et al.*, “Generation of high power short RF pulses using an X-band metallic power extractor driven by high charge multi-bunch train”, in *Proc. IPAC’19*, Melbourne, Australia, May 2019, pp. 734–737, 2019. doi:10.18429/JACoW-IPAC2019-MOPRB069

[6] S. Weatherly *et al.*, “Standing wave dielectric disk accelerating structure design and low power measurements”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 1073, p. 170283, 2025. doi:10.1016/j.nima.2025.170283

[7] G. Rijal, M. Shapiro, and X. Lu, “Dark current simulations in accelerating structures operating with short RF pulses”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 1440–1443, 2024. doi:10.18429/JACoW-IPAC2024-TUPR11

[8] G. Rijal, M. Shapiro, and X. Lu, “Analytical and numerical studies of dark current in radiofrequency structures for short-pulse high-gradient acceleration”, *Phys. Rev. Accel. Beams*, vol. 28, p. 111301, 2025. doi:10.1103/w9mh-3klh

[9] G. Rijal, M. Shapiro, X. Lu, S. Doran, and J. Power, “RF breakdown and dark current studies in short-pulse acceleration”, in *Proc. NAPAC’25*, Sacramento, CA, USA, Aug. 2025, pp. 847–850, 2025. doi:10.18429/JACoW-NAPAC2025-WEP079

[10] H. Xu, M. A. Shapiro, and R. J. Temkin, “Measurement of internal dark current in a 17 GHz, high gradient accelerator structure”, *Phys. Rev. Accel. Beams*, vol. 22, p. 021002, 2019. doi:10.1103/PhysRevAccelBeams.22.021002