Measurement of internal dark current in a 17 GHz, high gradient accelerator structure

H. Xu,^{*} M. A. Shapiro, and R. J. Temkin

Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

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We report the measurement of the internal dark current in a 17 GHz, high gradient accelerator cavity and its comparison with theory. The cavities were fabricated from copper and had a sidewall that was either uncoated or coated with diamondlike carbon or TiN. The dark current was monitored by a downstream detector and by detectors behind two small slits made in the cavity sidewall. With an increasing gradient, the downstream current increased monotonically, as expected for field emission. The variation of the internal, side dark current was not monotonic but showed the onset of peaks at gradients near 45 and 65 MV/m. These were identified as the N = 2 and N = 1 single point multipactor resonances. The total internal dark current was estimated at ~15–30 A. The magnitude of the internal dark current and its dependence on the gradient were in good agreement with simulations using the CST code as well as an inhouse code. Processing to a higher gradient, ~90 MV/m, eliminated the N = 2 mode, but the N = 1 mode persisted. The coated sidewall cavities showed the same multipactor resonances as the uncoated structure. However, at the highest gradient achieved in testing, the coated structures showed a modest reduction in the internal dark current.

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I. INTRODUCTION

Dark current is a current of electrons generated by field emission from the accelerator walls, in distinction from the primary current propagating along the accelerator axis [1]. Dark current is an unwanted effect in the operation of a high gradient accelerator structure. If dark current electrons are captured in phase along the beamline, the electrons will gain kinetic energy and interfere with the primary electron beam [2]. Dark current electrons that are captured and accelerated to high kinetic energy can collide with the accelerator cavity inner surfaces, especially the high electric field regions (irises, for example), and cause damage [3,4]. Dark current that propagates along the accelerator axis can be measured by Faraday cups installed at the ends of the accelerator structure. Spectrometers can analyze the electron energy distribution contributing to the study of the high gradient performance of the structure [5-8] and the detailed breakdown processes [9].

In addition to the dark current that propagates along the axis, which is called the downstream dark current, there is an internal dark current that remains inside the individual accelerator cavities. This internal dark current is well known to exist in accelerator structures but has been the subject of a very limited number of studies. Simulation efforts have been carried out to study the dynamics of the internal dark current [2,10–12]. These studies showed evidence of an internal dark current, although the portion of the electrons that could be captured, transmitted along the beam axis, and thus detected by the downstream Faraday cups was found to be a small fraction of all of the electrons generated.

We report an experimental and theoretical investigation of the internal dark current generated at the sidewall in a high gradient accelerator structure. Electrons generated at the wall can be accelerated by microwave fields near the wall, returning to the wall and colliding with it. These electrons may generate a large number of secondaries if the conditions for resonant multipactor ionization are present. This internal dark current will produce a cloud of electrons near the sidewall. It will also cause heating of the structure and may result in outgassing and ionization of gas atoms. For these reasons, the study of the internal dark current is potentially a very important issue in research aimed at increasing the gradient of electron accelerators. Theories and experiments on the multipactor were reported in the early days of accelerator research, especially for the S band and below [13-16]. These studies investigated electron multipactor effects caused by the axial electric field and produced a downstream dark current. The present study differs in considering the internal dark current excited by

haoranxu@mit.edu

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radial fields near the cavity sidewall. Recently, Cahill *et al.* showed that an internal dark current may limit the achievable gradient in the operation of cryogenic copper accelerator cavities [17].

In this paper, we introduce our 17 GHz high power test experimental setup and then describe the internal dark current simulations using the commercial code CST [18] as well as our own code. High power experimental results for the accelerator structure with uncoated and coated sidewalls will be reported next, followed by discussion and conclusions.

II. EXPERIMENTAL SETUP

The block diagram of the single cell high power experimental test stand at MIT is shown in Fig. 1. The microwave source is a traveling wave relativistic klystron working at a center frequency of 17.145 GHz with a bandwidth of 20 MHz, produced by Haimson Research Corporation [19]. It is capable of generating a microwave pulse of 10–1000 ns with a maximum power of 25 MW at 76 dB gain. We use a 4.4 dB hybrid at the rf output end of the klystron to protect the klystron from power reflection that may occur during structure rf breakdown. The structures are installed in a test vacuum chamber that is isolated from the klystron vacuum by a ceramic window.

The diagnostics of the experiment include the forward and backward rf power signals, the downstream current monitor signal (DC-D), and two side current monitor signals (DC-S1 and DC-S2). The forward and backward rf power was sampled by a 65 dB attenuation directional coupler and two Schottky detector diodes. Breakdown events were easily identified from the two side dark current signals and the downstream dark current signal.

The test stand had been previously used for the high power testing of the MIT disk-loaded waveguide (DLWG) accelerator structure [20]. That structure had a measured breakdown rate of $\sim 1.2 \times 10^{-2}$ per pulse per meter at a gradient of 89 MV/m with a pulse length of



FIG. 1. MIT standing wave high power test stand schematic diagram. 1, microwave synthesizer; 2, signal modulator; 3, solid state amplifier; 4, 17 GHz klystron; 5, 4.4 dB hybrid; 6, directional coupler; 7, detector diodes; 8, mode launcher; 9, structure under test; 10 and 11, side dark current monitors; 12, downstream dark current monitor; 13, digital oscilloscope.

100 ns. The DLWG structure is scaled from the X-band SLAC design with a 0.215 aperture-wavelength ratio, as shown in Fig. 2.

III. MULTIPACTOR SIMULATION

The electric and magnetic field distributions of the structure in Fig. 2 are displayed in Fig. 3. It can be seen that the central cell has the highest axial electric field, and the ratio of the magnitude of the maximum electric field in the three cells is approximately 1:2:1.

A. MIT particle tracking simulation code

We developed a 2D particle tracking code to simulate the electron trajectories at the sidewall of an accelerator cavity. The code uses the electric and magnetic field calculation results exported from CST Microwave Studio. The code was 2D, because, for a standing wave structure working in the TM₀₁ mode (transverse) and π mode (longitudinal), there is no electric or magnetic field exerting an azimuthal force on the electron, so that we needed only to calculate the electron trajectories in the longitudinal plane. The structure geometry determines that the surface radial electric field on the sidewall is not zero but has a small, sinelike profile



FIG. 2. Axisymmetric view of the 17 GHz MIT-DLWG test structure.



FIG. 3. MIT-DLWG π mode electric (a) and magnetic (b) field distribution.



FIG. 4. Electric and magnetic field distribution on the surface of the central cell sidewall at an acceleration gradient of 100 MV/m.

(Fig. 4). It is this small but nonzero radial electric field that causes the electron multipactor and the internal dark current. The magnetic field along the sidewall is nearly constant along the *z* direction (Fig. 4). At z = 0, the radial variation of the axial electric field takes the shape of a zeroth-order Bessel function, peaking at the beam axis and equaling zero at the sidewall. When an electron is released from the sidewall surface, the multipactor can be initiated and driven by the configuration of the electric and magnetic fields at the sidewall of the cavity. We used the Rung-Kutta-Fehlberg algorithm (RKF45) for the calculation of the electron dynamics [21].

Figure 5 shows the longitudinal (rz) plane for the multipactor electron trajectory simulation. For a given acceleration gradient (E_g) and emission site on the sidewall (z_0) , an electron with an initial kinetic energy E_0 and emission angle γ_0 was released at an rf phase of φ_0 . The origin O of the z axis along the sidewall was set at the equator of the central cell sidewall. In the code, for each (E_g, z_0) parameter pair, we did a 2D sweep of γ_0 and φ_0 to look for electron impacts and multipactor resonance. The secondary electron yield (SEY) of the returning electron was calculated using Vaughan's model [22]. When the SEY exceeded unity, the multipactor was observed.

We used N to represent the number of rf cycles elapsed between the release of the electron and the collision of the electron back onto the surface. We classified the multipactor into different modes according to the different trajectory patterns. Within the range of acceleration gradient up to 350 MV/m, we found three modes of single



FIG. 5. Electron trajectory simulation geometry.



FIG. 6. Sample trajectories of the second-order one-point MP (a) at 45 MV/m, the first-order one-point MP (b) at 72 MV/m, and the first-order two-point MP (c) at 250 MV/m.

surface multipactor: the first and the second order of the one-point multipactor and the first order of the two-point multipactor, as illustrated in Fig. 6. In the one-point multipactor mode, the electron returns to the emission site after one (first order, N = 1) or two (second order, N = 2) rf cycles, and the typical excursion distance of the electron away from the sidewall surface is very small, only about 0.1 mm. For the two-point multipactor (N = 0.5), the electron impacts between two locations equally distant from the sidewall midpoint (origin O) with a period of half an rf cycle. It is worth pointing out that the trajectories are formed under the influence of both the electric and magnetic fields near the sidewall and that the resonance is lost when the magnetic field is turned off in the calculation. In Fig. 6(a), the electron is released with 2 eV initial energy and returns to the surface with an energy of 105 eV.

In this way, on the $E_g - z_0$ plane, multipactor susceptibility diagrams can be generated to illustrate where the accelerator cell is prone to the multipactor of various modes. For example, a diagram made with initial kinetic energy $E_0 = 2$ eV is shown in Fig. 7. Each point on the diagram represents an electron trajectory of the corresponding multipactor mode with the electron released at a location z_0 and an acceleration gradient on axis of E_g . The color contour shows the SEY of the returning electron.



FIG. 7. Multipactor susceptibility diagram for one-point multipactor modes (N = 1, 2). The color bar shows the value of the secondary electron yield.



FIG. 8. Multipactor susceptibility diagram for the two-point multipactor (N = 0.5).

The SEY depends on the energy and the incident angle of the electron returning to the sidewall. The larger the SEY, the more serious the multipactor is likely to be. It can be seen that the second-order one-point multipactor (N = 2 mode) turns on at a relatively lower gradient (~45 MV/m), and then the first-order one-point multipactor (N = 1 mode) appears at a higher gradient (~65 MV/m) and covers a wider range of the gradient. The span along the *z* axis of these two multipactor modes covers most of the sidewall length. The first-order two-point multipactor (N = 0.5) happens at a far higher gradient (≥ 200 MV/m) which cannot yet be attained in our experiments (Fig. 8), but it does imply that the multipactor problem may still serve as a barrier for achieving a very high acceleration gradient in the future.

The internal dark current will form an electron cloud at the sidewall of thickness l and electron density n_m . This layer will have an effective dielectric constant:

$$\varepsilon = 1 - \frac{n_m}{n_c},$$

where n_c is the cutoff density at 17.1 GHz ($n_c = 3.6 \times 10^{18} \text{ m}^{-3}$). Assuming that the layer is uniform, it will detune the cavity frequency by an amount of

$$\frac{\Delta\omega}{\omega} \approx C \cdot \frac{l}{R_0} \cdot \frac{n_m}{n_c},$$

where the cavity radius $R_0 = 7.58$ mm and constant $C \approx 0.03$. We estimate that $l/R_0 \sim 10^{-2}$ and $n_m/n_c \sim 10^{-2}$, so that the detuning is much less than Q_l^{-1} , where our cavity loaded quality factor $Q_l \approx 3000$. The cavity is thus predicted to remain in resonance even after the formation of the electron cloud in a multipactor discharge. Calculations at other frequencies (2–110 GHz) also predict that the sidewall electron cloud does not grow large or dense enough to cause detuning and power reflection from the cavity.

B. CST **PIC** simulations

To verify the results from our electron trajectory calculations, we did particle-in-cell (PIC) simulations in CST



FIG. 9. Longitudinal (a) and transverse (b) cross section of the MIT-DLWG model in CST. 1, the sidewall section assigned with SEE properties; 2, the electron emission point source. Electrons travel to the indicated sidewall section and initiate multipactor.

Particle Studio. The MIT-DLWG structure was modeled with a section of the central cell sidewall assigned with secondary electron emission (SEE) properties (Fig. 9). The section is a strip 0.60 mm wide by 5.68 mm long. The choice of using just a portion of the sidewall, a strip, was necessary in order to limit the calculation size but is also reasonable, since the forces in the azimuthal direction are very small.

In the simulation, a square pulse microwave input filled the structure in the TM_{01} mode. A point source of electrons located on the iris where the electric field was maximum emitted electrons upon each rf cycle. The emitted electrons traveled to the sidewall surface, and the multipactor on the structure sidewall was monitored by calculating the collision and emission current on the sidewall section with SEE properties. The electrons released from the point source served only as the seeding electrons, the current of which is very small compared to the collision current generated by multipactor.

Figure 10 displays the simulated acceleration gradient and multipactor current vs time. The multipactor current value in the plot is the total current, obtained by scaling the current generated in the azimuthal length of the strip section



FIG. 10. CST PIC simulation multipactor current and gradient vs time.



FIG. 11. Central cell design of the MIT-DLWG-S structure. Two thin slits are opened on the sidewall, opposite to each other. 1, the sidewall section assigned with SEE properties; 2, the side dark current monitor; 3, the electron emission point source.

(0.60 mm) to the total central cell circumference (47.50 mm). The major result of this calculation is that the multipactor current is not a monotonically increasing function of the accelerator gradient. Instead, it shows a spike when the gradient increases to about 45 MV/m, and then a reduction to a low value, followed by a sharp rise at a gradient of 65 MV/m. The large current seen above 65 MV/m causes the simulation to terminate. The values of the gradient at which the multipactor turns on in Fig. 10 agreed well with the prediction from the susceptibility diagram (Fig. 7). The effects of the first- and the second-order one-point multipactor were thus observed in both simulations.

IV. MODIFIED STRUCTURE DESIGN AND SIMULATION

In order to directly measure the internal dark current in high power operation, we built a modified version of our MIT-DLWG structure, designated as the MIT-DLWG-S structure (Fig. 11). The new structure has two thin side slits on the central cell sidewall so that the dark current can be extracted directly from the central cell into a Faraday cup detector (the side dark current monitor). The slits are each 0.51 mm wide (along the azimuth) and 5.68 mm long (along the *z* direction) and are separated by 180°.

Because the slits cause small perturbations in the electric and magnetic fields in the structure, we conducted additional simulations of the dark current and multipactor for the MIT-DLWG-S structure in CST Microwave Studio. At the same gradient, the peak magnetic field in the MIT-DLWG-S structure is 1.2 times the peak magnetic field in the MIT-DLWG structure, and the maximal electric field on the slit is 1.3 times the peak electric field on the MIT-DLWG structure sidewall. For a 210 ns rf pulse, the maximum pulsed temperature rise in the MIT-DLWG-S structure is around 50 K for a 90 MV/m gradient.

One purpose of these PIC simulations in CST Particle Studio was to see whether the secondary electrons can

effectively transmit through the side slits and reach the side dark current monitors. As indicated in Fig. 11, a point electron source is assigned at the location where the electric field peaks on the iris. Some of the released electrons will gain energy and travel to the sidewall. A section of the central cell sidewall, including one side of the slit, is assigned as a SEE emitter (Vaughan's model) [22]. At certain gradients, the multipactor generates an electron cloud on the surface of this sidewall section. The central angle α of the SEE section is set to 20°, which we found to be large enough to model all of the electrons that could reach the side dark current monitor outside the slit.

At a fixed gradient of 60 MV/m, the N = 1 mode of the multipactor was identified on the sidewall section assigned with the SEE property, and a saturated multipactor current (the collision current onto the surface) of 5.0 A was obtained in the simulation after 2 ns. Considering $\alpha = 20^{\circ}$, we estimate the total multipactor current on the entire sidewall to be 90 A. Meanwhile, the side dark current monitor received a current of 12.5 mA. This current is generated only from one side of the slit; therefore, we would expect 25 mA of side dark current if there should be a 90 A multipactor current inside the structure. These simulations were used to scale the dark current measured in the side Faraday cups in the experiment to approximate values for the full side internal dark current in the structure, and the scaling factor is roughly 3600. The simulation also verified that the structure was not detuned due to the electron cloud formed on the surface of the sidewall section.

V. STRUCTURE FABRICATION

An assembly drawing of the MIT-DLWG-S structure is shown in Fig. 12. Six stainless steel rods clamp the copper plates of the structure sections. Also shown in Fig. 12 are the copper downstream dark current monitor (DC-D) and the two stainless steel side dark current monitors (DC-S1/2). All the current monitors are fastened onto the structure using ceramic fasteners, so that they are electrically isolated from the metal structure. The central cell of the structure was fabricated in three versions: an uncoated copper cell, a cell coated with diamondlike carbon (DLC), and a cell



FIG. 12. Assembly drawing of the MIT-DLWG-S structure, axisymmetric view, showing the three dark current monitors.

coated with titanium nitride (TiN). The coatings were nominal 20-25 nm thick in order to lower the surface secondary electron yield [23-25] while maintaining the structure rf properties unchanged. Only the sidewall of the central cell was coated, while the surfaces of the end plates as well as the irises were uncoated copper. Separate experimental tests were conducted with the MIT-DLWG-S in which the central cell sidewall was uncoated (copper). DLC coated, and TiN coated, respectively. The purpose of the coated structures was to investigate a possible reduction in the internal dark current through the low SEE properties of the DLC and TiN surfaces. All of the parts were fabricated via direct machining in the MIT shop with the exception of the slit features, which were made by wire EDM. The structures that were coated were sent for coating to Acree Technologies Inc. of Concord, California, USA. Masking was used to limit the coating to the sidewall.

VI. EXPERIMENTAL RESULTS

A. Cold test

The cold test of all three structures was carried out using a vector network analyzer and a TM_{01} mode launcher. Figure 13 shows the measured reflection coefficient of the MIT-DLWG-S structure around the π -mode resonance. We measured the quality factors and the resonant frequency of the structure, as shown in Table I. We measured the quality factors and the resonant frequency of the structure, as shown in Table I. In the table, Q_0 measures the Ohmic loss in the cavity, Q_{ext} measures the power loss into the external circuit, and the loaded (total) quality factor Q_1 is defined as $Q_1^{-1} = Q_0^{-1} + Q_{ext}^{-1}$. We measured the axial electric field distribution using the nonresonant method [26], with a dielectric bead perturbing the field along the beam axis. The result agreed well with the simulation, as shown in Fig. 14.



FIG. 13. MIT-DLWG-S S_{11} measurement result of the π -mode resonance (uncoated version).

TABLE 1. Comparison of the cold test resonant frequency and the quality factors to the results of simulation in CST.

	Frequency (GHz)	Q_0	$Q_{\rm ext}$	Q_l
CST	17.149	6998	6974	3493
Uncoated	17.120	5584	5817	2849
DLC coated	17.143	5714	5980	2922
TiN coated	17.153	5670	6471	3022

B. High power test: Early processing results

A sample pulse at the test stand (Fig. 1) is displayed in Fig. 15. The high power microwave pulse was a flattop pulse of length 210 ns. The power coupled inside the structure varied during the pulse length but was stable to within $\pm 10\%$ over a ~120 ns time interval. In the following discussion of the experimental results, we refer to the gradient as the peak value reached inside the structure during the pulse. The repetition rate of the high power testing was typically one pulse per second. We limited consecutive breakdowns to a maximum of ten before decreasing the microwave power level to prevent further breakdowns. The structures were each tested for about 2.2×10^5 high power pulses. The downstream dark current (DC-D) and the two side dark current (DC-S1/2) signals were monitored and the traces recorded.

A typical set of measured dark current traces for all three dark current monitor signals is shown in Fig. 16 for a gradient of 65 MV/m for the uncoated MIT-DLWG-S structure. For the downstream dark current, we find that the signal rises monotonically with an increasing gradient. This is a typical and expected result. As conditioning proceeded, at the same level of gradient, the amplitude of the downstream dark current tended to decrease. After processing to about 2.2×10^5 pulses, we measured the downstream dark current amplitude vs acceleration gradient, and the plot is shown in Fig. 17 for all three of the tested structures—the uncoated structure and the two coated structures. There was no significant difference between



FIG. 14. Comparison of the MIT-DLWG-S field profile measurement result and the CST simulation result (uncoated version).



FIG. 15. Sample pulse of the forward and the backward (reflected) power and the calculated structure acceleration gradient vs time.



FIG. 16. MIT-DLWG-S high power test sample traces of the acceleration gradient (blue), downstream dark current (red), and two side dark currents (magenta and green) vs time.



FIG. 17. Downstream dark current amplitude measured vs acceleration gradient for central cells with an uncoated copper sidewall; a diamondlike carbon (DLC) coated sidewall and a TiN coated sidewall.

the downstream dark current amplitude levels for these three different structures.

The traces of the side dark current vs time were significantly different from the downstream dark current traces. For all of the dark current measurements, the



FIG. 18. Side dark current traces showing possible multipactor modes at different peak acceleration gradient levels.

waveforms of the two side dark current detectors were highly repeatable and always nearly identical, so that we can specialize to either one of the detectors. The remarkable feature of the side dark current traces was that the amplitude of the side dark current did not increase monotonically as the gradient increased but showed spikes and plateaus at certain gradient levels, as clearly seen in Fig. 16. The first spike occurs as the gradient reaches a value of ~45 MV/m, and the second spike occurs at ~65 MV/m. The field emission theory would predict a monotonic increase with the gradient and therefore cannot explain these results.

Figure 18 shows a sequence of side dark current traces at increasing values of the peak acceleration gradient for the uncoated structure. For a peak gradient below 45 MV/m, the side dark current was at the noise level [Fig. 18(a)], but, starting at 45 MV/m, we observed a sudden turn-on of the side current with the profile shown in Fig. 18(b). With an increasing gradient, the side dark current trace increased in pulse duration. The side dark current also developed two spikes, one at the beginning and one at the end of the pulse. A second threshold behavior of the side dark current occurred when the structure gradient increased from 65

to 66 MV/m. The spike at the end of the pulse, as shown in Fig. 18(e), grew much larger with a tiny increase in the gradient. The variation of these traces with the gradient was highly reproducible. It is remarkably different from the downstream dark current.

The observed sudden increase of the side dark current amplitude around 45 and 65 MV/m gradient corresponds almost exactly with the turn on of the N = 2 and N = 1multipactor modes, respectively, predicted by the simulations. We plotted the measured side dark current vs the acceleration gradient and compared the result with the CST PIC simulation result, as shown in Fig. 19. The measured value of the side dark current was scaled to the appropriate value for the entire central cell sidewall, using the scaling factor derived in the CST simulations (Fig. 10). The experimental measurement agrees very well with the PIC simulation predictions for the first- and the second-order multipactor resonances.

C. High power test: Later processing results

As the conditioning progressed, the side dark current spikes that occurred at 45 MV/m gradually disappeared, but the sudden increase of the side dark current around 65 MV/m remained. A typical set of dark current measurement traces taken at the end of the MIT-DLWG-S processing (~ 2.2×10^5 pulses) and at a peak gradient $\sim 90 \text{ MV/m}$ is shown in Fig. 20. These traces may be compared with the results shown in Fig. 16, where the structure was processed only up to ~ 66 MV/m. In Fig. 20, we can see that the N = 2 multipactor resonance has disappeared, since there are no longer side dark current spikes at \sim 45 MV/m gradient. We also see that the side dark current is still spiking near 65 MV/m gradient. These spikes are seen on both the rise and fall of the gradient curve. In the center of the pulse, at gradient levels above \sim 75 MV/m, there is a decrease in the side dark current. Again, this is counterintuitive if we suppose that the side dark current comes from field emission. The reason for the side dark current decrease can be explained as the structure



FIG. 19. The measured side (internal) dark current vs the acceleration gradient compared with the CST simulated multi-pactor current.



FIG. 20. MIT-DLWG-S high power test sample traces of the acceleration gradient (blue, peak \sim 90 MV/m), downstream dark current (red), and two side dark currents (magenta and green), at the end of the processing.

exceeding the N = 1 mode multipactor barrier as the acceleration gradient ascends or descends through a value of 75 MV/m.

Figure 21 shows a set of side dark current traces taken on the last day of the high power test of the structure with an uncoated central cell sidewall. The side dark current spikes at around 45 MV/m gradient had already disappeared through conditioning, while the N = 1 mode remained, starting up near 65 MV/m, as the only visible part of the side dark current in Fig. 21.

D. High power test: Coated structures

Observations of the side dark current showed very similar features for the structure tests with coated central cell sidewall structures when compared with the uncoated structures. At an early stage of conditioning, side dark current spikes (N = 2 mode) were observed at ~45 MV/m in both the DLC and TiN coated structures, and they faded away when the structures were processed to higher power microwave pulses. The sharp increase of the side dark current amplitude at a higher gradient near 65 MV/m (N = 1 mode) was consistently observed. At the end of the tests, at a gradient ~90 MV/m, the measured side dark current amplitude was in the range of 4–9 mA for all structures, which scales to ~15–30 A total multipactor current on the entire central cell sidewall.

We took one side dark current trace from the last day of processing $(2.2 \times 10^5 \text{ pulses})$ for each of the three structures, and a plot of the side dark current vs the gradient for all three structures is shown in Fig. 22. The most interesting difference between the structures occurs at the highest gradient values. The N = 1 mode of the multipactor turns on at about 62–66 MV/m in the three structures. At a gradient above 75 MV/m, the coated central cell sidewalls consistently yielded less side dark current, compared with the uncoated sidewall, although the differences are modest. Figure 22 also shows the highest gradient achieved in testing to 2.2×10^5 pulses, with the TiN coated structure reaching the highest value, 92 MV/m.



FIG. 21. Side dark current traces taken at the end of the testing of the uncoated structure, showing the elimination of the N = 2 mode through processing.



FIG. 22. Variation of the side dark current to the increase of the calculated acceleration gradient within one pulse.

E. Breakdown rate vs gradient

After 2.2×10^5 pulses, all three versions of the structure achieved a breakdown rate level of ~ 10^{-1} per pulse per meter in the gradient range of 80–90 MV/m. Because the structures were far from being fully conditioned, it was unclear whether the coatings had an effect on reducing the structure breakdown rate. A future study with greater processing of the structure would be needed to determine the function of the SEE suppression coatings in breakdown events.

VII. DISCUSSION AND CONCLUSIONS

To our knowledge, this is the first detailed study of the internal dark current vs gradient in a high gradient accelerator structure. The internal dark current was extracted directly from the side of the high gradient accelerator cell. The results show clear evidence of multipactor in a normal conducting, high gradient accelerator structure.

Experimental measurements showed the first- and the second-order one-point multipactor, as predicted by CST PIC simulations as well as by our in-house 2D particle tracking code. Very good agreement was obtained between the theory and experiment for the value of the gradient at which first- and the second-order one-point multipactor is initiated.

An estimated sidewall total multipactor current of ~30 A was derived by scaling from the PIC simulation result for an acceleration gradient of ~90 MV/m. The simulations showed that the average collision kinetic energy of the electrons with the sidewall was only about 60–70 eV, so the thermal power deposition from the multipactor was several kilowatts. This power level is negligible compared to the surface Ohmic heating (megawatt level) in a room temperature high gradient accelerator structure. A possible technique for mitigating multipactor is the use of a magnetic field to suppress the multipactor oscillation, as demonstrated in past research experiments [27–30]. This could be a useful approach for a future investigation with our structures.

The internal dark current could be a factor in the rate of breakdowns at a very high gradient. It is possible that the intense interaction of low energy electrons and the material surface can give rise to serious outgassing and local gas ionization. Internal dark current can also grow to form a dense cloud of electrons that can send electrons towards the axis through space charge and rf forces. As the electrons travel away from the sidewall, they witness larger rf electric fields, and they can gain energy much faster in this process. Such electrons could contribute to the breakdown rate. These effects would be of interest for further investigation.

Two types of coatings, diamondlike carbon and titanium nitride, were applied separately in tests on the central cell sidewall of the structure in an effort to reduce the surface secondary electron yield. Above a gradient of 75 MV/m,

both types of coating helped to modestly reduce the secondary electron emission on the central cell sidewall. These results are in qualitative agreement with the known lower values of the SEY of these materials [23–25]. Further research at a high gradient would be needed to fully understand the detailed effect of these coatings on achieving reliable operation at a high gradient. The test with the titanium nitride coating achieved the highest structure acceleration gradient after the same level of processing. Figure 20 illustrates the changes in the structure side dark current that result from processing the structure up to the highest gradients shown in Fig. 22. In Fig. 20, the N = 2multipactor resonance has disappeared, since there are no longer side dark current spikes at \sim 45 MV/m gradient. We attribute the decrease in the multipactor to a reduction in the SEY resulting from the processing. However, we cannot estimate the reduced SEY values that result from the processing and therefore cannot use these reduced SEY values for additional multipactor calculations. Previous research had been performed coating the entire inner surface of an accelerator cell with titanium nitride; in that case, the results were worse with the coating than without it [31]. It can be inferred that coating only the sidewall of an accelerator cell has the potential to increase the high gradient performance, but coating the surfaces where the electric field is high with dielectrics will have negative effects.

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- A. Chao, K. H. Mess, M. Tigner, and F. Zimmermann, Handbook of Accelerator Physics and Engineering (World Scientific, Singapore, 2013).
- [2] C. K. Ng, N. Folwell, A. Guetz, V. Ivanov, L. Q. Lee, Z. Li, G. Schussman, and K. Ko, Simulating dark current in NLC structures, Nucl. Instrum. Methods Phys. Res., Sect. A 558, 192 (2006).
- [3] P. B. Wilson, Frequency and pulse length scaling of RF breakdown in accelerator structures, in *Proceedings of the* 19th Particle Accelerator Conference, Chicago, IL, 2001 (IEEE, Piscataway, NJ, 2001), Vol. 1, pp. 509–511.
- [4] Z. Li, C. K. Ng, T. Higo, A. Grudiev, A. Candel, M. Gerbaux, L. Ge, K. Ko, G. Schussman, S. Döbert, W. Wuensch, S. Matsumoto, and K. Yokoyama, Dark current simulation for the CLIC T18 high gradient structure, in *Proceedings of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009* (IEEE, Piscataway, NJ, 2009), WE5PFP046, pp. 2101–2103.
- [5] J. W. Wang, RF properties of periodic accelerating structures for linear colliders, SLAC, Stanford, Report No. SLAC-REP-339, 1989.

- [6] H. Matsumoto, M. Akemoto, H. Hayano, T. Naito, and S. Takeda, High gradient experiment by ATF, in *Proceedings of the 8th Symposium on Accelerator Science and Technology, Wako, Saitama, Japan, 1991* (Ionics Publishing Co., Ltd., Tokyo, Japan, 1991), pp. 141–143.
- [7] J. Norem, V. Wu, A. Moretti, M. Popovic, Z. Qian, L. Ducas, Y. Torun, and N. Solomey, Dark current, breakdown, and magnetic field effects in a multicell, 805 MHz cavity, Phys. Rev. ST Accel. Beams 6, 072001 (2003).
- [8] T. Higo, T. Taniuchi, M. Yamamoto, J. Odagiri, S. Tokumoto, H. Mizuno, K. Takata, I. Wilson, and W. Wuensch, Highgradient experiment on X-band disk-loaded structures, Reports No. CERN-SL-93-39-RFL, CM-P00061154, 1993.
- [9] M. Jacewicz, V. Ziemann, T. Ekelöf, A. Dubrovskiy, and R. Ruber, Spectrometers for RF breakdown studies for CLIC, Nucl. Instrum. Methods Phys. Res., Sect. A 828, 63 (2016).
- [10] K. L. Jensen, Y. Y. Lau, D. W. Feldman, and P. G. O'Shea, Electron emission contributions to dark current and its relation to microscopic field enhancement and heating in accelerator structures, Phys. Rev. ST Accel. Beams 11, 081001 (2008).
- [11] H. Xu, M. A. Shapiro, and R. J. Temkin, Dark current study of a standing wave disk-loaded waveguide structure at 17 GHz, in *Proceedings of NAPAC'16, Chicago, 2016* (JACoW, Geneva, Switzerland, 2017), WEPOB31, pp. 971–973.
- [12] K. L. F. Bane, V. A. Dolgashev, T. Raubenheimer, G. V. Stupakov, and J. Wu, Dark currents and their effect on the primary beam in an X-band linac, Phys. Rev. ST Accel. Beams 8, 064401 (2005).
- [13] V. J. Vanhuyse, J. L. Verhaeghe, and J. Turf, The multipactor effect in a linear electron accelerator, Nuovo Cimento 10, 721 (1958).
- [14] A. J. Hatch, Suppression of multipacting in particle accelerators, Nucl. Instrum. Methods 41, 261 (1966).
- [15] D. Proch, D. Einfeld, R. Onken, and N. Steinhauser, Measurement of multipacting currents of metal surfaces in RF fields, in *Proceedings of the Particle Accelerator Conference, Dallas, TX, 1995* (IEEE, New York, 1995), Vol. 3, pp. 1776–1778.
- [16] C. Bourat and J. M. Joly, On multipactor effect in a 600 MHz RF cavity used in electron linear accelerator, IEEE Trans. Electr. Insul. 24, 1045 (1989).
- [17] A. D. Cahill, J. B. Rosenzweig, V. A. Dolgashev, Z. Li, S. G. Tantawi, and S. Weathersby, rf losses in a high gradient cryogenic copper cavity, Phys. Rev. Accel. Beams 21, 061301 (2018).
- [18] CST, http://www.cst.com.
- [19] J. Haimson and B. Mecklenburg, A 71 dB gain, high efficiency relativistic klystron using a high current linear accelerator traveling wave buncher output structure, *AIP Conf. Proc.* 691, 34 (2003).
- [20] B. J. Munroe, J. X. Zhang, H. Xu, M. A. Shapiro, and R. J. Temkin, Experimental high gradient testing of a 17.1 GHz photonic band-gap accelerator structure, Phys. Rev. Accel. Beams 19, 031301 (2016).
- [21] J. H. Mathews and K. D. Fink, Runge-Kutta-Fehlberg method (RKF45), in *Numerical Methods Using Matlab* (Prentice-Hall, Upper Saddle River, NJ, 2004).

- [22] R. M. Vaughan, Secondary emission formulas, IEEE Trans. Electron Devices **40**, 830 (1993).
- [23] Y. Saito, Vacuum system of high-energy accelerators: Electrical breakdown in vacuum, Rev. Bras. Aplic. Vác. 22, 39 (2003).
- [24] V. Baglin, I. R. Collins, J. Gómez-Gońi, O. Gröbner, B. Henrist, N. Hilleret, J-M. Laurent, M. Pivi, R. Cimino, V. V. Anashin, R. V. Dostovalov, N. V. Fedorov, A. A. Krasnov, O. B. Malyshev, and E. E. Pyata, Experimental investigations of the electron cloud key parameters, LHC-Project-Report-313, 1999.
- [25] A. F. Leontowich and A. P. Hitchcock, Secondary electron deposition mechanism of carbon contamination, J. Vac. Sci. Technol. B **30**, 030601 (2012).
- [26] C. W. Steele, A nonresonant perturbation theory, IEEE Trans. Microwave Theory Tech. 14, 70 (1966).
- [27] 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).

- [28] C. Chang, J. Verboncoeur, S. Tantawi, and C. Jing, The effects of magnetic field on single-surface resonant multipactor, J. Appl. Phys. **110**, 063304 (2011).
- [29] C. Jing, C. Chang, S. H. Gold, R. Konecny, S. Antipov, P. Schoessow, A. Kanareykin, and W. Gai, Observation of multipactor suppression in a dielectric-loaded accelerating structure using an applied axial magnetic field, Appl. Phys. Lett. **103**, 213503 (2013).
- [30] C. Jing, S. H. Gold, R. Fischer, and W. Gai, Complete multipactor suppression in an X-band dielectric-loaded accelerating structure, Appl. Phys. Lett. **108**, 193501 (2016).
- [31] V. Dolgashev, S. G. Tantawi, Y. Higashi, and T. Higo, Status of high power tests of normal conducting single-cell structures, in *Proceedings of the 11th European Particle Accelerator Conference, Genoa, 2008* (EPS-AG, Genoa, Italy, 2008), MOPP083, pp. 742–744.