DARK CURRENT STUDY OF A STANDING WAVE DISK-LOADED WAVEGUIDE STRUCTURE AT 17 GHz*

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Abstract

We present calculations of the dark current in a high gradient accelerator with the intent of understanding its role in breakdown. The initial source of the dark current is the field emission of electrons. For a 17 GHz single-cell standing wave disk-loaded waveguide structure, the 3D particle-in-cell simulation shows that only a small portion of the charge emitted reaches the current monitors at the ends of the structure, while most of the current collides on the structure surfaces, causing secondary electron emission. In the simulation, a two-point multipactor process is observed on the side wall of the cell due to the low electric field on the surface. The multipactor approaches a steady state within nanoseconds when the electric field is suppressed by the electron cloud formed so that the average secondary electron yield is reduced. This multipactor current can cause the ionization of the metal material and surface outgassing, leading to breakdown. We report first results from an experiment designed to extract dark current directly from an accelerator cell from the side through two slits. First results show that the dark current behavior deviates from the field emission theory.

INTRODUCTION

One of the factors that are considered to affect the performance of a normal conducting high gradient accelerator is dark current. Once captured, dark current can become part of the beam that is being accelerated by the cavities and degrade the beam quality. Also, secondary electrons and X-ray photons can be generated by the collision of dark current electrons onto the structure surfaces.

Dark current in an accelerator cavity is initiated by field emission, and processes such as secondary electron emission (SEE) and multipactor (MP), assuming an average secondary electron yield (SEY) above unity, can add to the ultimate dark current measured in experiments. Our study investigates MP driven by the electric field on the surface of the accelerator structure side wall. The RF electric field on the side wall surface is perpendicular to the surface, but the parallel field turns on where there is a displacement away from the side wall. When the field emission electrons hit the side wall, secondary electrons can be expelled by the perpendicular field, accelerated by the parallel field, and pulled towards the side wall again with a period of half an RF cycle.

The dark current from an accelerator cavity is often measured by current monitors at the ends of the structure, and the results are usually fitted using the Fowler-Nordheim (FN) formula for field emission to acquire estimation for field enhancement factor. However, assuming the dark current is only generated through field emission, only a small fraction of the current makes it to the current monitors and the fractional value can vary with the gradient level. On the other hand, whether the current being measured all comes from field emission can be questioned. A more direct measurement of the dark current from a high gradient accelerator cell can provide us with more distinct information about the dark current generation mechanism.

The particle-in-cell (PIC) simulation method serves as an efficient way to study the dynamics of dark current, including the generation of SEE and the formation of MP. All of the PIC simulations mentioned in this work were carried out in CST Particle Studio [1].

SIMULATION

A 3D model of the standing wave single cell structure with a resonant frequency of 17.1 GHz is built, based on the MIT Disk-Loaded Waveguide (MIT-DLWG) structure [2], as shown in Fig. 1. The TM_{01} mode microwave power is fed in from the left through the circular waveguide and the ratio of the peak amplitude of the electric field on the beam axis in the three cells is about 1:2:1. SEE using Furman's model [3] is calculated only for the central cell (within the red rectangle), since the field strength is low in the other cells. On the surface of each of the irises facing the central cell, we create a source of electrons by selecting a ring shaped area (indicated by arrows) which sees the maximum of the electric field when the cavity is under high gradient operation. The emission current is decided by FN field emission theory.

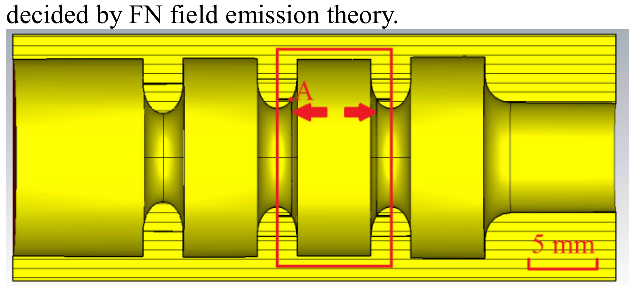

Figure 1: MIT-DLWG structure model.

The field enhancement factor β value is determined from the previous high power test of the MIT-DLWG structure. An immediate calculation using the downstream dark current monitor (placed at the right end in Fig. 1) measurement result gives a β value of 81. However, the escape ratio, which is defined as the percentage of the field emission electrons that reach the current monitors at the ends of an accelerator structure, needs to be considered to correct this calculation. Fig. 2 shows the escape

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ratio calculated for different gradient levels from simulations using β=81 (these simulations do not include the SEE calculation). It can be seen that most of the current is blocked by the structure. Our calculation shows β=56 for our accelerator structure after the calibration of the downstream dark current using the escape ratio curve.

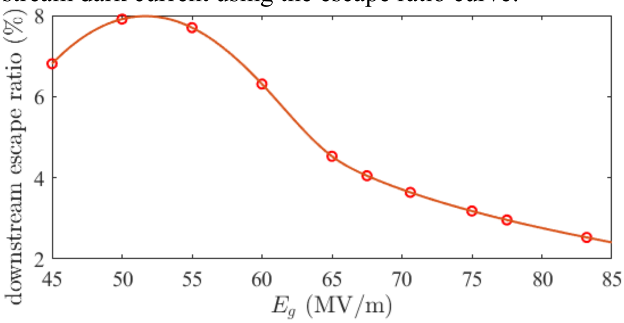

Figure 2: Downstream escape ratio curve.

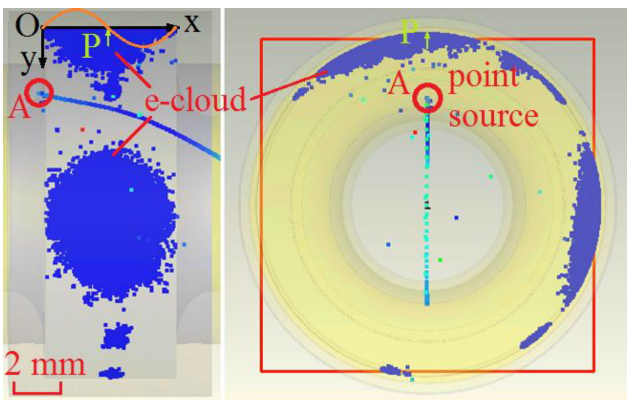

Figure 3: Side view and front view of the central cell with electron cloud formed on the structure side wall.

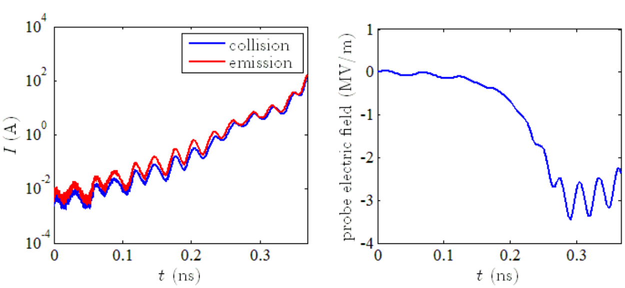

Figure 4: Left: the electron collision and emission current on the side wall surface; right: electric field seen at probe P in Fig. 3.

The simulation for MP is performed with 80 MV/m gradient. The emission source is modeled as a single point source (point A in Fig. 1 and Fig. 3) due to the fast increase of secondary electron population. The simulation shows that within nanoseconds, an electron cloud is formed on the structure side wall surface, and the collision and emission current exceed 100 A, as shown in Fig. 4 (left). It is also observed that the current has an alternating current component oscillating at a frequency twice the RF frequency, indicating an MP. This MP is driven by the electric field distribution in the vicinity of the side wall. The normal electric field along the side wall is qualitatively described by the sine like orange curve in Fig. 3. The amplitude of this field is ~3.5 MV/m. Probe P is placed midway between the cell end plates where there is zero electric field before the build-up of the electron cloud. When the electron cloud is formed, the probed field drops from zero to a direct current electric field of around -3 MV/m, presumably shifted by the space charge field. Although the emission and collision current were still growing when the calculation was terminated, a steady state electric field was attained locally within the electron cloud.

The collision current on the cell side wall can give rise to a series of physical processes, such as outgassing and material ionization, contributing to a higher breakdown probability. It is also important to point out that the above mentioned MP process cannot be eliminated by conditioning the structure as long as the SEY curve of the side wall surface material favors the maintaining of the MP. Experiments are needed to confirm the existence of such an MP process and its relation with the initiation of breakdown.

EXPERIMENT

A single cell standing wave structure (MIT-DLWG-S) is designed and fabricated to resemble the MIT-DLWG structure as well as extract dark current directly from the central cell through two narrow slits opened on the side wall and into the side dark current monitors (DC-S1/S2), as shown in Fig. 5. The downstream dark current monitor is labelled as DC-D. The cold test shows that the structure has a resonant frequency of 17.134 GHz for π-mode with a loaded quality factor of 2804 and the field measurement result agrees with the simulated profile (see Fig. 6).

The high power testing of MIT-DLWG-S structure uses a 17.1 GHz traveling-wave relativistic klystron built by Haimson Research Corporation. The structure has taken more than one hundred thousand shots, and a sample of power traces (210 ns pulse) is shown in Fig. 7.

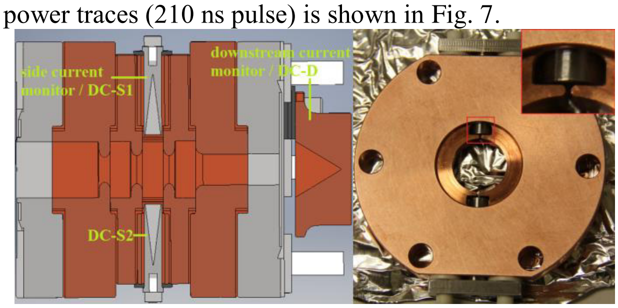

Figure 5: Cross section view of MIT-DLWG-S structure and the central cell plate with side current monitors.

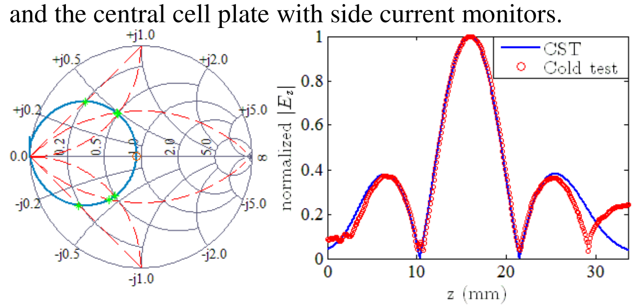

Figure 6: MIT-DLWG cold test S_{11} measurement and field measurement results.

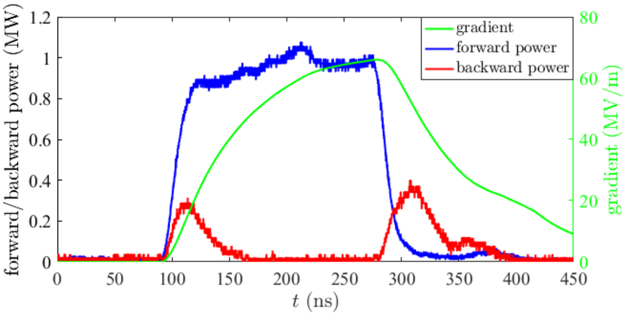

Figure 7: Forward / backward power traces and the structure gradient.

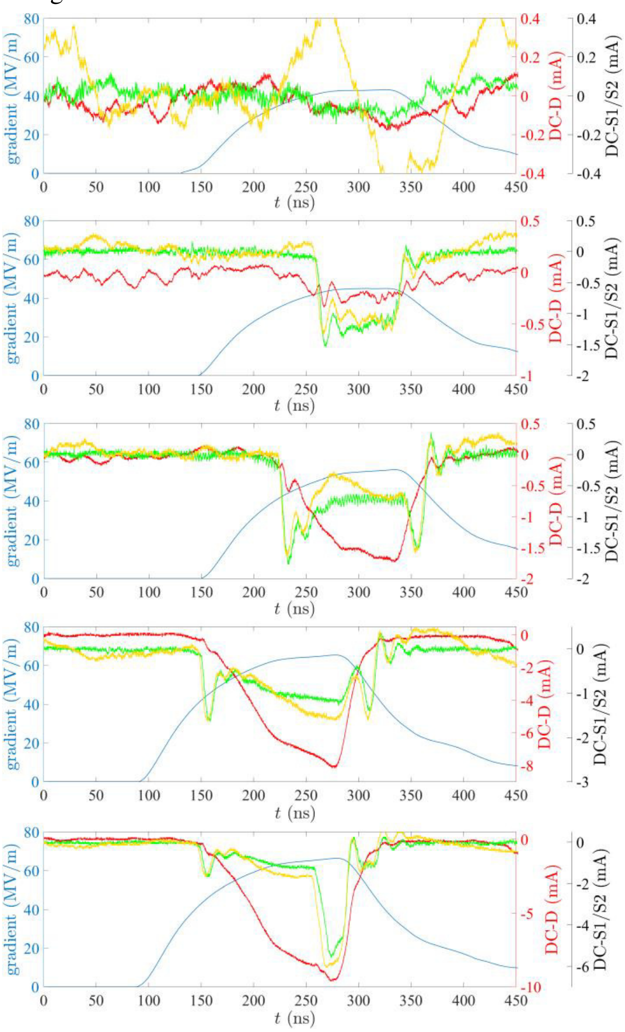

Figure 8: DC-D current (red) and DC-S1 (green) / S2 (yellow) current traces and gradient (blue) for 43, 45, 56, 65 and 66 MV/m peak gradient pulses.

The dark current behavior observed is displayed in Fig. 8. The downstream dark current increases from about 0.2 mA at 43 MV/m peak gradient to almost 10 mA at 66 MV/m, in line with expectations of Fowler Nordheim emission. The side dark current has a quite different behavior. DC-S1 current becomes observable at 25 MV/m peak gradient, then it rises continuously with the increase of forward power. At a peak gradient of around 45 MV/m, DC-S1/S2 current sees a jump from 0.1 mA to above 1 mA. When the forward power continues to increase, the DC-S1/S2 signal becomes longer in time and its central section begins to decrease, marked by the formation and the increasingly wider time separation of the two spikes with constant amplitude of 1.5 mA. It is noticed that the spikes always coincide with an instant gradient of about 45 MV/m. At 56 MV/m peak gradient, the amplitude of the central section of the DC-S1/S2 signal reaches a minimum and begins to rise, with a shape similar to that of the DC-D current signal. Finally another sudden rise of DC-S1/S2 current from 1.5 mA to 5 mA occurs at around 65 MV/m peak gradient. In the experiment, when the second sharp rise in DC-S1/S2 current appears, the breakdown events become more frequent.

In the experiment, although the discontinuities in the rise of the DC-S1/S2 current can be reflected in the DC-D signal trace, they do not lead to a similar threshold behavior in the latter. Also, the existence of the above mentioned current spikes and the decrease of the amplitude of the central section of the DC-S1/S2 current signal in the course of turning up the forward power cannot be explained by the field emission theory.

Each slit on the side wall takes up 1.1% of the cylindrical wall circumference, therefore we can estimate that a dark current of 0.46 A reaches the side wall for 66 MV/m peak gradient. The fact that the traces from the two side dark current monitors are almost identical indicates that the generation of dark current in such a structure is azimuthally symmetric.

CONCLUSIONS

A series of particle-in-cell simulations have been performed to examine the dark current behavior in the MIT-DLWG structure. To acquire an accurate value for the field enhancement factor, one needs to consider the escape ratio of the field emission current in the real structure. The simulations show that multipactor is established by secondary electron emission driven by the RF electric field on the cell side wall, and that an electron cloud is built up on the side wall surface during this process.

An experiment has been conducted to study the dark current with a more direct measurement method. Field emission theory does not explain the discontinuities observed in the dark current measured on the side current monitors with increasing gradient. Further research is planned to study these phenomena.

REFERENCES

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[3] M. A. Furman *et al.*, "Probabilistic model for the simulation of secondary electron emission," *Phys. Rev. AB.*, vol. 5, no. 12, p. 124404, 2002.