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MEASUREMENT OF THE INTERNAL DARK CURRENT IN A HIGH GRADIENT ACCELERATOR STRUCTURE AT 17 GHz*

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Abstract

We report a study of internal dark current generation by multipactor inside a 17 GHz single cell standing wave disk-loaded waveguide accelerator structure. The multipactor takes place on the side wall of the central cell, driven by the local rf electric and magnetic fields. Theory indicates that a resonant multipactor mode with two rf cycles can be excited near 45 MV/m gradient and a single rf cycle multipactor mode near 60 MV/m. The accelerator structure had two thin slits opened on the side wall of the central cell to directly extract and measure the internal dark current. The dark current was measured as a function of the gradient up to a gradient of 87 MV/m. The experimental results agreed well with theory, showing the two predicted multipactor modes. To further study the effect of the central cell side wall surface properties on the structure performance, we conducted another two high power tests of the structure with the central cell side wall coated with diamond-like carbon and titanium nitride, respectively. Test results are reported and discussed.

INTRODUCTION

Dark current in an accelerator structure often refers to the additional current that is generated inside the structure from field emission. The dark current is usually an unwanted effect, because it adds to the noise of the beam signal, and can damage the structure irises if the dark current electrons are captured and gain high energy traveling along the beam line. Dark current is also a strong precursor of vacuum breakdown and is constantly monitored in high power testing of room temperature accelerator structures, by Faraday cups at the ends of the structures.

Studies on dark current simulation have shown that only a small portion of the dark current generated inside the accelerator structure can actually escape from the structure and get detected by the Faraday cups, and that the majority of the dark current electrons end up colliding on the inner surface of the structure [1]. Massive interaction of dark current electrons with the metal surfaces can cause various physical phenomena such as outgassing and gas ionization, which may be associated with breakdown initiation and render the study of internal dark current important. We studied the internal dark current behavior inside the MIT Disk Loaded Waveguide (DLWG) structure [2], a single cell standing wave normal conducting structure working at 17 GHz. We report several modes of electron multipactor that take place on the side wall of the central cell which witnessed the highest acceleration gradient. Such multipactor phenomena can be a serious source of internal dark current during the high gradient operation of the structure.

Prior work has shown that multipactor can take place at accelerator rf couplers and rf windows [3]. To calculate the expected multipactor inside an accelerator cell, we developed an in-house particle tracking code, using Runge-Kutta-Fehlberg method, to locate the different multipactor modes in a parameter space of multipactor location, acceleration gradient, rf phase, etc. To experimentally verify the multipactor behavior predicted and to measure the internal dark current in a more direct manner, a series of controlled high power tests of a modified structure was carried out, in which the structure central cell side wall was prepared and tested in three different versions: uncoated copper, diamond-like carbon (DLC) coated and titanium nitride (TiN) coated, respectively.

MULTIPACTOR MODES

The structure in which we studied the multipactor is indicated in Fig. 1. The ratio of the magnitude of the maximum axial electric field in the three cells is approximately 1:2:1 (π-mode), and we mainly looked at the physics in the central cell of the structure. In the vicinity of the central cell side wall, there exist the axial and radial components of the rf electric field as well as the azimuthal magnetic field. Although the magnitude of the electric field at the side wall is much smaller compared to the surface electric field on the iris or the acceleration gradient, it is crucial in driving the local electron multipactor. The field is shown in Fig. 2.

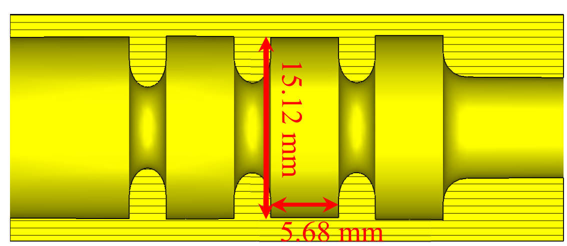

Figure 1: Axisymmetric view of the 17 GHz MIT-DLWG structure.

Because the structure works in a TM_{01} mode, there is no azimuthal electric field in the cell. The electrons inside the cell do not see azimuthal forces exerted by the rf electric or magnetic field. The 2-d multipactor trajectory calculation was carried out on the rOz plane, as shown in Fig. 3. An electron is released at an initial location z_0 on the side wall at an emission angle θ_0 to the normal and rf phase φ_0, with an emission kinetic energy of E_0. If the electron released can come back to the emission location after an integer

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number of rf periods and give rise to more than one secondary electron, a multipactor condition is met. We used the code to make a parameter sweep on the entire side wall along the axial direction, and over the acceleration gradient range achievable in our high power testing. Two multipactor modes, the $H = 1$ mode and the $H = 2$ mode, were identified, the trajectories of which are displayed in Fig. 4.

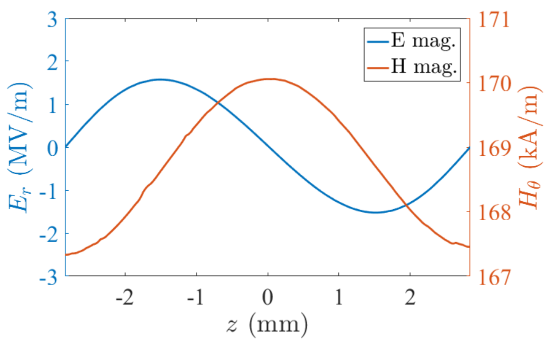

Figure 2: The axial distribution of the radial electric field magnitude and azimuthal magnetic field magnitude on the central cell side wall for an acceleration gradient of 45 MV/m (simulation in CST Microwave Studio [4]).

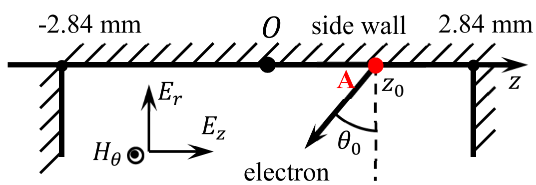

Figure 3: Multipactor calculation geometry.

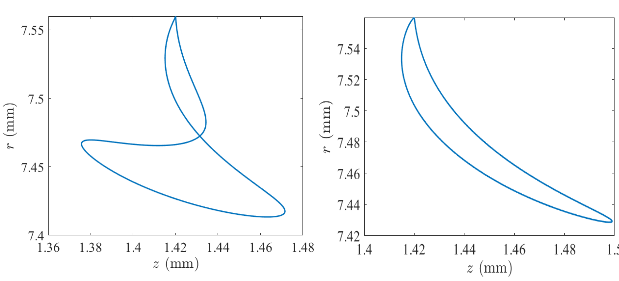

Figure 4: Multipactor trajectories for the $H = 2$ mode (left) at an acceleration gradient of 45 MV/m and the $H = 1$ mode (right) at 72 MV/m. In both trajectories, the electron is released at $z_0 = 1.42$ mm with an initial energy of 2 eV. Side wall is located at $r = 7.56$ mm.

As the acceleration gradient increases during a high power pulse, the mode that turns on first is the $H = 2$ mode, which means that the multipactor period takes two rf periods, as illustrated in Fig. 4 on the left. When the acceleration gradient gets to a higher level, the $H = 1$ mode appears. The multipactor of this mode has a resonance period of one rf cycle.

INTERNAL DARK CURRENT MEASUREMENT

In order to have a direct measurement of internal dark current, we designed a single cell standing wave structure based on the MIT-DLWG design, with the only modification being the two thin side slits opened on the side wall of the central cell along the beam axis, opposite to each other, as shown in the structure design in Fig. 5. Two Faraday cups are installed immediately outside the two slits to measure the internal dark current that escapes from the central cell through the slits. Also, a third Faraday cup measures the downstream dark current at the end of the structure.

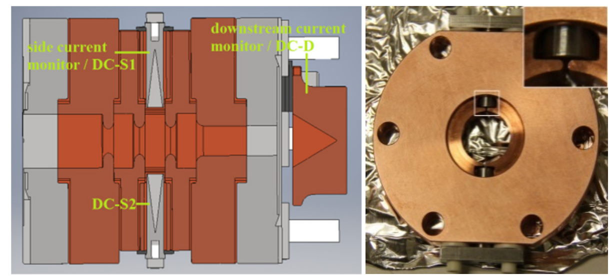

Figure 5: Accelerator structure for high power testing (left). Two Faraday cups, DC-S1/S2, measure the side dark currents, and another current monitor, DC-D, measures the downstream dark current; the thin slits on the side wall of the fabricated part (right).

The high power testing was conducted in MIT using a 17.1 GHz traveling wave relativistic klystron built by Haimson Research Corporation. Fig. 6 shows a typical set of traces observed during the experiment. During the high power pulse, the downstream dark current amplitude increased with the rise of the structure acceleration gradient as expected, but this was not the case for both the side dark currents. On either trace of the side dark current measurement, we observe two sharp rises of the side dark current amplitude, one at around 45 MV/m, and the other at about 65 MV/m. The measured gradient values of these two side dark current spikes agree very well with the values predicted by our particle tracking code. Also, the traces of both the side dark currents always took the same shape and had very similar amplitudes, which implied that the generation of such side dark currents was azimuthally symmetric over the cylindrical side wall of the cell.

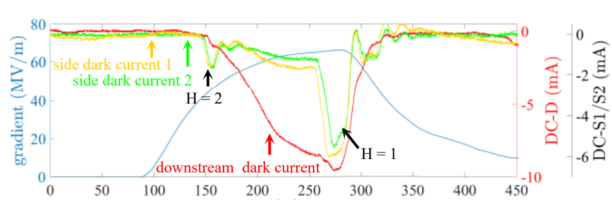

Figure 6: Sample traces of the structure acceleration gradient, downstream dark current and side dark currents. The high power microwave pulse is a square pulse with a pulse length of 210 ns.

EXPERIMENTS WITH COATED SIDE WALL

Multipactor behavior is very sensitive to the material surface conditions. In order to have a better understanding

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of the effect of multipactor on the accelerator structure performance, we prepared another two central cell side wall parts and had them coated with diamond-like carbon and titanium nitride, respectively. The coatings were a nominal 20-25 nm layer on top of the original copper surface, capable of changing the material surface secondary electron emission properties while maintaining the original rf properties of the structure. Note that only the side wall of the central cell was coated, while the endplates along with the irises where the rf electric field could be strong were still uncoated copper. Diamond-like carbon and titanium nitride both have been confirmed to be capable of reducing the secondary electron emission on the material surface [5]. For the high power testing of the different central cell side wall surface conditions, all the other parts of the structure were reused. Each of the high power tests lasted for about 2.2×10^5 pulses, and the highest acceleration gradients achieved for the three tests are listed in Table 1. At the end of each run, we swept the acceleration gradient and measured the downstream dark current (Fig. 7) as well as the side dark current (Fig. 8).

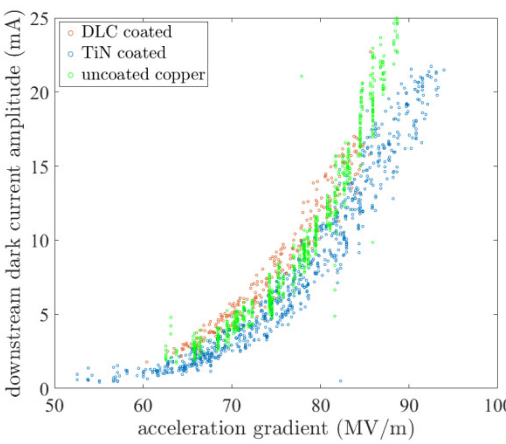

Figure 7: Downstream dark current amplitude measured at different acceleration gradient levels for the structures with different central cell side wall surface conditions.

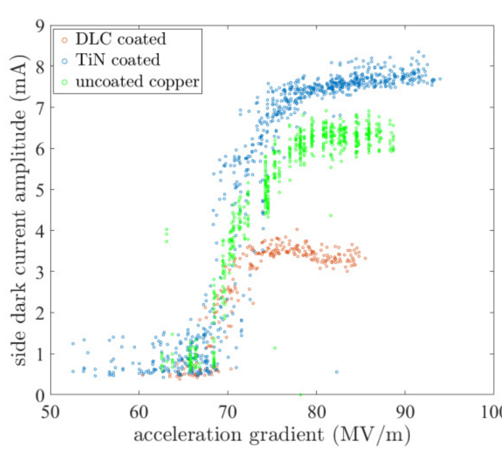

Figure 8: Side dark current amplitude measured at different acceleration gradient levels.

The downstream dark current measurement results for all the three tests showed similar amplitudes at comparable gradient levels, though the downstream dark current from the structure with an uncoated central cell side wall showed a notably higher rate of increase. The side dark current measurement results showed a consistent step-like increase of the side dark current amplitude around the gradient level of 72 MV/m. This is consistent with the sudden turn-on of the $H = 1$ mode of the multipactor on the central cell side wall surface. For all three tests, the $H = 2$ mode always appeared at an early stage of the high power testing and was consistently observed, and gradually disappeared during the conditioning. The amplitude of the $H = 1$ mode also tended to decrease over the conditioning period, but it never went away.

Of the three central cell side wall surface treatments, the diamond-like carbon coating was most efficient in reducing the secondary electron emission, while the uncoated part had a better performance than the one coated with titanium nitride, though the latter reached a higher acceleration gradient.

Table 1: Highest Acceleration Gradient Achieved

Structure	Gradient Achieved
uncoated copper	87 MV/m
DLC coated	89 MV/m
TiN coated	96 MV/m

CONCLUSIONS

An in-house code was developed to study the multipactor behavior in the MIT-DLWG structure and two modes of multipactor on the structure central cell side wall surface were identified for the acceleration gradient range the structure achieved.

A standing wave single cell structure was designed to measure the internal dark current and to compare the results with the multipactor phenomena predicted in the theories. Both the $H = 1$ mode and the $H = 2$ mode were observed in the high power experiments.

Diamond-like carbon and titanium nitride coatings were tried on the structure central cell side wall surface, and the diamond-like carbon coating was confirmed to have the best performance suppressing the surface secondary electron emission.

REFERENCES

[1] K. L. Bane, V. A. Dolgashev, and G. V. Stupakov, "Simulation of dark currents in X-band accelerator structures," in *Proc. EPAC'04*, Geneva, Switzerland, Jul. 2004, paper TUPKF059, pp. 1081-1083.

[2] B. J. Munroe *et al.*, "Experimental high gradient testing of a 17.1 GHz photonic band-gap accelerator structure," *Phys. Rev. AB.*, vol. 19, no. 3, p. 031301, 2016.

[3] C. K. Ng *et al.*, "Multipacting simulation of accelerator cavities using ACE3P," in *Proc. PAC'13*, Pasadena, CA, USA, Sep. 2013, paper MOPBA18, pp. 216-218.

[4] CST, http://www.cst.com

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL033

[5] S. Michizono *et al.*, "Secondary electron emission of sapphire and anti-multipactor coatings at high temperature," *Appl. Surf. Sci.*, vol. 235, no. 1-2, pp. 227-230, 2004.