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MULTIPACTOR ELECTRON CLOUD ANALYSIS IN A 17 GHz STANDING WAVE ACCELERATOR CAVITY*

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Abstract

Theoretical predictions of single-surface one-point multipactor modes have been confirmed in experiments with a 17 GHz standing wave single cell disk-loaded waveguide accelerator structure operating in the gradient range of 45-90 MV/m. Theoretical calculations were performed of the frequency detuning introduced by the multipactor electron cloud on the cell side wall for different electron cloud thicknesses and densities. We found that the detuning ($\Delta\omega/\omega$) due to the electron cloud was too small to cause significant power reflection in room temperature copper cavities, but may be significant in cavities cooled to cryogenic temperatures. A similar cavity design with the central cell taking an elliptical axial profile was tested under high power, and the results showed that the multipactor modes observed previously in a cell with a straight axial profile were eliminated under this elliptical design. We used a dc-biased current monitor to study the side dark current energy spectrum, and the result is presented.

INTRODUCTION

Internal dark current refers to the electrons that are generated and then terminated inside an accelerator cavity. It is differentiated from the conventional dark current that exits the accelerator at the upstream or downstream ends. Much information regarding the origin and formation of the internal dark current cannot be retrieved since, as has been observed in multiple particle-in-cell (PIC) simulations, only a small portion of the total dark current generated can eventually exit the accelerator structure and be captured by the Faraday cups upstream or downstream. The study of internal dark current emphasizes on understanding the sources of the dark current, especially those in addition to the field emission, the termination of the dark current inside the accelerator cavity, and the subsequent physical processes that can potentially affect the cavity performance.

Apart from the field emission of electrons at the locations where the metal surface witnesses intense rf electric field, e.g. the irises forming the beam aperture, one important mechanism of dark current generation is multipactor. In one of our previous experiments testing a standing wave single cell disk-loaded waveguide (DLWG) accelerator structure at 17 GHz, we observed two single surface one-point multipactor modes, the $N = 1$ and $N = 2$ modes, on the side wall of the central cell in the acceleration gradient range of 45 MV/m to 90 MV/m [1]. In a recent theoretical study of the dark current inside travelling wave accelerator structures designed for CLIC prototype testing, electron trajectories for multipactor modes were identified at a gradient of 100 MV/m [2].

In our DLWG structure, when the multipactor resonances are excited, CST [3] PIC simulations indicate that a layer of electron cloud is formed over the cylindrical side wall, marking a state of equilibrium by multipactor secondary electron emission and space-charge suppression of the emission. It is of interest to understand the effect of the electron cloud loading inside the accelerator cavity, whether or not this layer of electrons can cause cavity detuning or microwave breakdown. The dependence of these effects on the accelerator operating frequency is also of great interest.

DETUNING BY ELECTRON CLOUD

We consider that the side wall multipactor forms a uniform electron cloud that can be represented by a dielectric layer with thickness l and constant relative permittivity ϵ_r:

$$\epsilon_r = 1 - \frac{\omega_{p,e}^2}{\omega^2} \qquad (1)$$

where the electron cloud plasma frequency $\omega_{p,e}$ is calculated from the electron cloud density n_e using $\omega_{p,e}^2 = n_e e^2/(\epsilon_0 m_e)$. CST eigenmode solver was used to calculate the resonant frequencies of the accelerator cell loaded with such a dielectric layer. We are interested in the resonant frequency detuning ($\Delta\omega/\omega$) introduced by the electron cloud.

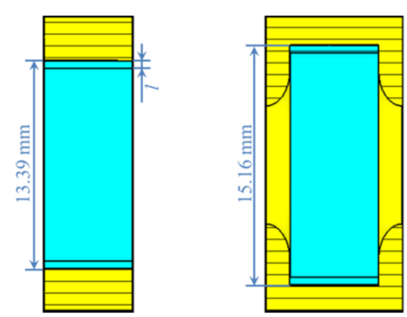

Figure 1: CST eigenmode solver 17.136 GHz models for pillbox TM_{010} mode (left) and the accelerator cavity TM_{01} mode (right) with 180 degree phase advance in the direction of the beam axis between the boundaries (π-mode).

Two types of models were used in the calculation, as shown in Fig. 1. The calculation for the basic case of a pillbox TM_{010} mode serves as the benchmark of the calculation for the realistic accelerator cavity operating at TM_{01} mode and π-mode.

For the pillbox case, the detuning can be given conveniently by the Slater perturbation theorem:

$$\frac{\Delta\omega}{\omega} = \frac{p_{0,1}^2}{3} \cdot \frac{\omega_{p,e}^2}{\omega^2} \cdot \left(\frac{l}{R}\right)^3 \qquad (2)$$

where $p_{0,1}$ denotes the first zero point of Bessel function $J_0(x)$, and R the cell radius. The detuning is proportional to

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the electron cloud density and the cubic power of the thickness-radius ratio.

There is no analytical solution for the case of the real accelerator cell (Fig. 1, on the right). The detuning vs. electron cloud density was therefore calculated using CST Microwave Studio and is plotted for different thicknesses in Fig. 2 for the 17.136 GHz case. The results in Fig. 2 have a similar functional form to Eq. (2), with an approximate linear dependence of detuning on density and a dependence on cloud thickness proportional to $(l/R)^{2.65}$. This difference of the power of the dependence on the thickness-radius ratio is due to the fact that in the real accelerator cell, the beam aperture introduces a radial electric field on the side wall that decays towards the beam axis.

One way to evaluate the seriousness of detuning is to compare it with the reciprocal of the total, or loaded, quality factor Q_l. When the detuning approaches this value or even surpasses it, there is substantial reflection of the rf power back towards the generator. For the real case of our DLWG structure, at an acceleration gradient of 80 MV/m, both the multipactor electron trajectory calculation and CST PIC simulation give an electron cloud thickness estimate of 0.15 mm. Combining this thickness with our experiment results, we estimate the electron cloud density to be ~2×10^{17} m^{-3}, which causes a negligible detuning $\Delta\omega/\omega$ ~ 2×10^{-6}. For comparison, the low power test of our DLWG structure (critical coupling) showed that a detuning of 4.4×10^{-5} would cause 5% power reflection.

FREQUENCY SCALING OF DETUNING

To discuss the accelerator cavity detuning by the electron cloud layer loaded on the cell side wall, we start by rewriting the relativistic Lorentz force equation using variables normalized by frequency: $\phi = \omega t$, $\boldsymbol{\xi} = \omega \boldsymbol{x}$, $\boldsymbol{e} = \boldsymbol{E}/\omega$ and $\boldsymbol{b} = \boldsymbol{B}/\omega$, into the form:

$$\frac{\mathrm{d}}{\mathrm{d}\phi}\left(\frac{\boldsymbol{\beta}}{\sqrt{1-\beta^2}}\right) = -\frac{e}{mc}\left[\boldsymbol{e}(\boldsymbol{\xi},\phi) + \frac{\mathrm{d}\boldsymbol{\xi}}{\mathrm{d}\phi}\times \boldsymbol{b}(\boldsymbol{\xi},\phi)\right] \quad (3)$$

Note that $\boldsymbol{\beta} = \dot{\boldsymbol{x}}/c = c\cdot\mathrm{d}\boldsymbol{\xi}/\mathrm{d}\phi$ does not depend on frequency. This frequency independent equation holds not only for electron multipactor trajectory calculation, but can be used in calculating the final equilibrium state with stable electron cloud formed as well. In other words, the same state of multipactor modelled by Eq. (3) can readily be scaled to any frequency, and $\boldsymbol{e}(\xi,\phi)$ is the sum of rf and dc electric fields. As a result, for the same mode of multipactor, such as the $N = 1$ mode, the dc electric field formed by the electron cloud scales linearly with frequency $E_{dc} \propto \omega$; in the same way, $l \propto \omega^{-1}$. If we then use the relation:

$$E_{dc} = -\frac{e n_e l}{\epsilon_0} \quad (4)$$

We find the scaling of the electron cloud density to be in the form $n_e \propto \omega^2$.

With the frequency scaling laws of the physical quantities we have derived, one can instantaneously tell from Eq. (2) that the detuning is simply frequency independent:

$$\frac{\Delta\omega}{\omega} \propto \omega^0 \quad (5)$$

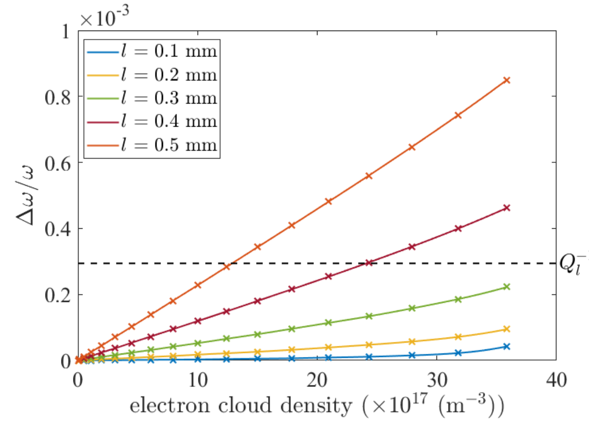

Figure 2: Resonant frequency detuning as a function of both the electron cloud density and the layer thickness at 17.136 GHz.

This result was actually confirmed in our CST PIC simulations for electron cloud formation at 2.856 GHz, 17.136 GHz and 110.0 GHz due to the $N = 1$ mode multipactor. In the simulation, we used field probes to measure the change of the dc electric field shift in the vicinity of the side wall to determine the values for l and n_e.

Combined results from CST PIC and eigenmode simulations showed that the detuning values for all three cases were consistently ~1×10^{-6}, in very good agreement with Eq. (5). For room temperature accelerator cavities of the same design, the loaded quality factor conforms to the relation $Q_l^{-1} \propto \omega^{1/2}$. Then it can be inferred that for the same mode of multipactor, the electron cloud detuning has less influence if the accelerator structure works at a higher frequency. For the $N = 1$ multipactor mode we discussed above, there is no serious additional power reflection induced by the onset of the electron cloud for the cases of all three frequencies. The reason is that for a resonant frequency of 2.856 GHz, the lowest of the three, CST Microwave Studio showed that a detuning of 1.5×10^{-5} was needed to cause 5% power reflection. At cryogenic temperature, however, accelerator cavities can have very large quality factors [4], and the multipactor electron cloud loading can become a significant issue. At 2.856 GHz, simulation showed that a critically coupled cavity with intrinsic quality factor $Q_0 = 8.5\times10^4$ for an operation temperature of 40 K would reflect 5% of the incident power if the structure was detuned by 3.6×10^{-6}. This is very close to our predicted detuning value, considering that the detuning is frequency independent. Although an accelerator structure is usually over-coupled at cryogenic temperature, this comparison of simulation results exemplifies the fact that the multipactor electron cloud loading can be an important effect for accelerators working at cryogenic temperature.

ELLIPTICAL SIDE WALL EXPERIMENT

The elliptical profile of an accelerator cell side wall has been known to mitigate one-point multipactor resonances. We designed a single cell standing wave accelerator structure with the central cell taking an elliptical profile (Fig. 3)

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to study the variation of the internal dark current behavior caused by this change of side wall shape design.

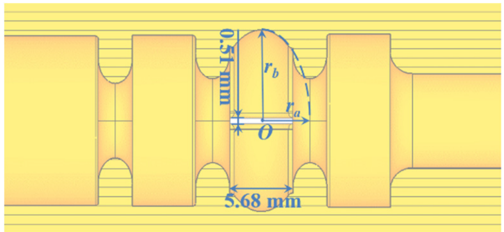

Figure 3: 17 GHz single cell standing wave structure with the central cell side wall being elliptical. Two slits are opened on the side wall, opposite to each other.

In the high power experiment, the internal dark current was measured by extracting the dark current generated inside the central cell through the two side slits opened on the side wall and received by a current monitor with dc voltage bias. The pulsed power was generated by a 17.145 GHz traveling wave relativistic klystron produced by Haimson Research Corporation. One set of oscilloscope traces is displayed in Fig. 4(b), where it can be seen that on the side dark current traces, the spikes we used to see marking the multipactor resonances (Fig. 4(a)) are nowhere to be found. The amplitudes of the side dark currents are much smaller than that measured in the structure with a cylindrical straight side wall.

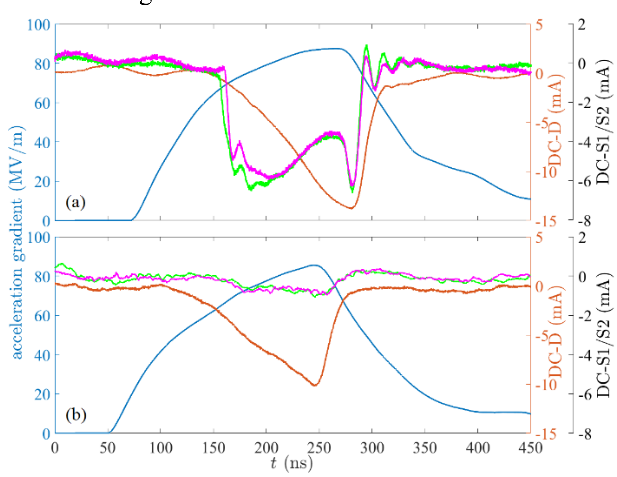

Figure 4: Downstream dark current (DC-D, orange) and side dark currents (DC-S1/S2, magenta and green) plotted in reference to the calculated acceleration gradient (blue) for the structure with cylindrical straight (a) and elliptical (b) side wall design.

In order to clarify the energy spectrum of the electrons forming the side dark current, we applied a series of dc voltages (within ±160 V) on the side dark current monitor and observed the changes in the amplitude of the side dark current, as shown in Fig. 5. The steep variation of side dark current amplitude in the bias voltage range of ±30 eV indicates that the majority of the electrons with energy less than 160 eV fall into the energy range of 0 – 30 eV. The amount of side dark current electrons that carry a kinetic energy less than 160 eV account for about half the total side dark current.

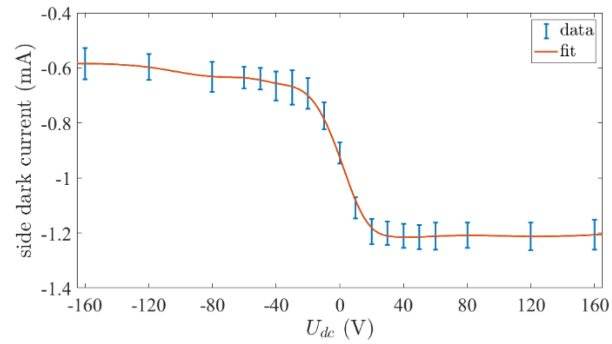

Figure 5: Measurement results and spline fitting of the side dark current amplitudes under dc bias voltages on the side dark current monitor at 85 MV/m gradient.

CONCLUSIONS

Theory efforts have been made to study the electron cloud layer formed over the surface of an accelerator cell side wall by modelling the electron cloud as a layer of dielectrics with the permittivity being that of uniform plasma reacting to external microwave fields. Using the experimental as well as CST PIC simulation results at 17.136 GHz, we find the detuning caused by the $N = 1$ multipactor electron cloud negligible. But this detuning mechanism can become serious when the cavity operates with a high quality factor e.g. at cryogenic temperature.

The theoretical calculation was extended to 2.856 GHz and 110.0 GHz. The resonant frequency detuning caused by the electron cloud layer generated by the same multipactor mode is essentially frequency independent, indicating an advantage for room temperature accelerators that operate at a higher rf frequency.

High power testing of a single cell standing wave accelerator structure with an elliptical side wall profile designed for the central cell showed that the previously seen $N = 1$ and $N = 2$ modes of multipactor in the structure with a cylindrical central cell side wall were absent. Energy spectrum analysis using a dc biased side dark current monitor indicated that half of the side dark current was consisted of electrons with kinetic energy less than 160 eV, which were likely to be generated via secondary electron emission.

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