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THRESHOLD IN FILLING FAILURE OF RF CAVITY CAUSED BY BEAM LOADING IN MULTIPACTOR*

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Abstract

A pulsed RF cavity would be heavily detuned caused by beam loading of multipactor current in the RF filling process. Multipactor zone would be expended by several times than that in static states with assumptions of fixed voltage and no beam loading. The dynamic of multipactor in the RF filling process was simulated by coupling with parameters of external circuit with the developed simulation code, and test in experiments with a parallel-plates resonator. Threshold of RF voltage, which means the lower boundary of peak voltage of multipactor zone, had been quantified with different cavity parameters. When we increased the gap length, the measured threshold became larger due to the ionization in background gas. Then the secondary emission factor would be increased in simulation for consistence with the experiment results. Additionally, some multipactor phenomenon could not be predicted precisely because the simulation code didn't take account of ionization. The hysteresis of phase and energy of ionization electrons would be a new driving factor for the growth of multipactor in certain conditions.

BEAM LOADING IN MULTIPACTOR

Multipactor is a common phenomenon in microwave system. Mostly, it is harmful, and should be suppressed in accelerating structure. In superconducting cavities, multipactor could lead to temperature rise in a small region and subsequently thermal breakdown. There are several ways to suppress this phenomenon: cavity shape optimization, external electrical or magnetic field, coating, grooving, and conditioning. Furthermore, a predicting method is useful to avoid severe breakdown.

In simulation with small current assumptions, the limitation of current grow-up will lead to a saturation when the voltage equals to the first crossover with unity secondary emission yield (SEY) [1]. In high-Q cavity, with consideration of external circuit, beam loading effect could be a more critical factor rather than space charge limitation.

In a pulsed high-Q RF accelerator, after RF turns on, the rising of electrical field or voltage will cross the "multipactor susceptible zone" (also called existence zone for multipactor discharge) in the RF filling process. The threshold in the topic sentence means the lower boundary of expected peak voltage that can fill the cavity successfully. This means that higher cavity voltages can reduce possibility of multipactor breakdown. Therefore, a high-Q pulsed RF system have larger multipactor zone than that derived from stable state conditions. On another hand, in actual high-Q RF systems, when the multipactor occurs during the RF filling process, the transient change of the peak value of the electromagnetic field is not only affected by the parameters of the power source, but also by the motion behavior of the secondary electrons. Because of beam loading, the secondary electron current may cause serious detuning of the cavity, which leads to the failure of the RF power filling.

In this paper, we introduced a two-side parallel-plates model and developed some codes to predict whether multipactor breakdown would happen in a RF filling process. With simulation codes with combination of secondary electronic dynamics and external circuit, the quantitative relationship between the threshold and RF parameters had been studied. Then we describe some simulation and experimental results about multipactor breakdown caused by beam loading effect.

SIMULATION

Circuit Model and Codes Preparation

The simulation code combined by 1-D electrons motion calculation with PIC method and circuit modelling is scripted in Fortran. The impacting and initial emission angle were taken account of in simulation. The sketch of simulation is shown in Fig. 1.

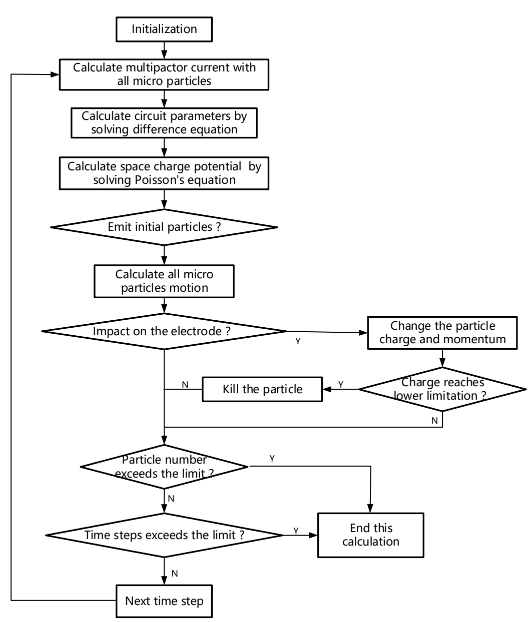

Figure 1: Sketch of simulation.

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The modelling of resonator and external circuit is shown in Fig. 2. The ideal current source could be realized by using circulators in RF power source.

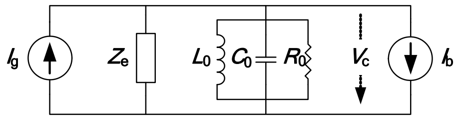

Figure 2: Simplified circuit model.

According to Kirchhoff's law, the parameters in the figure have the following relations:

$$\frac{\mathrm{d}\overrightarrow{V_c}}{\mathrm{d}t}+\left(\omega_{1/2}-j\Delta\omega\right)\overrightarrow{V_c}=\frac{1}{2}\omega_0\frac{r}{Q}\overrightarrow{I_g} \tag{1}$$

where $\omega_{1/2}$ is the half bandwidth. According to formula (1), dynamic of multipactor is effected by electrode material, RF structure, quality factor and detuning frequency.

To estimate the growth rate of the multipactor current, we followed the trajectories of weighted macro particles and adopted Vaughan's formula to calculate SEY [2]. Initial energy and angle were assigned randomly according to Kishek's formula in [3].

Two voltage values were determined in calculation of threshold voltage: if we could calculate the success of RF filling with expected voltage V_2 and failure with expected voltage V_1, and $V_2 - V_1 < 1$ kV, we chose the threshold voltage as the average value of V_2 and V_1.

With consideration of experimental setup, we choose several basement parameters in simulation with working frequency (f_0) as 72 MHz, gap width as 100 mm, Q_L as 1200, peak of SEY (δ_m) as 2.0.

Threshold Voltage Calculation Results

Some simulation results are shown in Fig. 3 and 4. Figure 3 showed that the threshold monotonously increased with the larger δ_m and larger Q_L, which correspond to larger reproduce rate and longer filling time. Figure 4 showed that the positive detuning slightly decreased the threshold. The main reason for this trend is that the phase of the secondary electron current delays behind the cavity voltage. However, it was not obvious in simulation because multipactor breakdown happened at the very beginning of RF filling progress and active detuning did not result in obvious phase deviation at the beginning. Furthermore, when we increased the gap width from 50 mm to 200 mm, the multipactor resonance condition had changed from 1st order to 3rd order. We can get a max deviation of threshold voltages about 2.5 kV by recalculating in multi approaching ways.

Figure 5 shows a failure example of filling failure caused by multipactor. After RF turning on, the voltage increased and reached the susceptible zone. Then multipactor current increased rapidly. Increment of the load decreased the voltage and introduced a phase-shifting between voltage and driving current. And multipactor current decreased to almost 0 in one RF period because the resonance condition between voltage phase and motion of electrons had been lost. The oscillation of voltage envelope could be observed occasionally in our experiments or other systems.

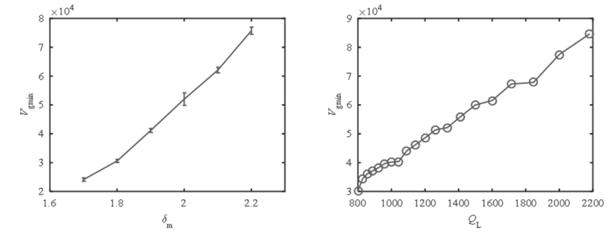

Figure 3: Simulated threshold voltages with different δ_m or different Q_L.

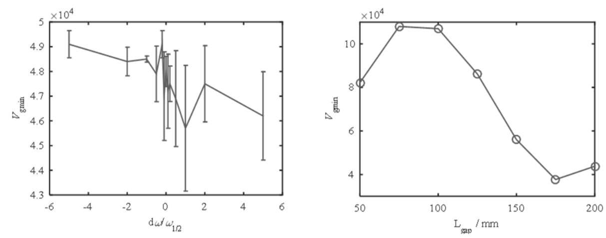

Figure 4: Simulated threshold voltage with different detuning frequencies or different gap width.

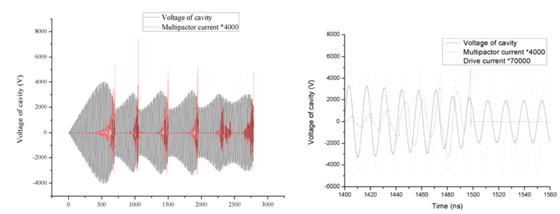

Figure 5: Cavity voltage and current in RF filling failure (left) and resonance condition lost (right: zoom in on left figure).

EXPERIMENTS

Experiment Setup

The main part of the experimental system was the RF cavity including parallel plate electrodes. The cavity was designed as an 1/4-λ coaxial cavity with working frequency as 72 MHz to match the existing power source. The parallel plates were made of oxygen free copper and the gap width could be adjustable from 50 mm to 150 mm. High vacuum environment could be obtained by a turbomolecular pump to10^{-4} Pa (no power) or maximal 10^{-3} Pa. Besides measuring cavity voltage by a pick-up, the intensity and timing characteristics of the multipactor is judged by measuring the signal of photomultiplier and measuring current in the central lower plate. The photomultiplier is an r4125 type made by Hamamatsu, Japan, with a signal rise time of 2.5 ns and a linear output of up to 100 mA. The Faraday cup consisted of a graphite collector with cone angle of 120 °, nylon isolator, electrons collimator and a grid sleeve. The grid is made of oxygen-free copper with a diameter of 6 mm, mesh number of 200 and transmittance of 25%. The collector is biased by a battery pack with a voltage of - 200 V.

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Results

Beside the success and failure of RF filling, an unexpected state concomitant with degassing and ionization was observed between certain expected voltages. This state could not be predicted precisely because the simulation code didn't take account of ionization. In Fig. 6, a filling success could happen with an expected voltage above 85 kV and a filling failure with an expected voltage below 50 kV. The critical upper and lower voltages were defined as 1st and 2nd threshold voltage relatively. In Fig. 7, transient behavior of voltage and current could be distinguished into 3 types either.

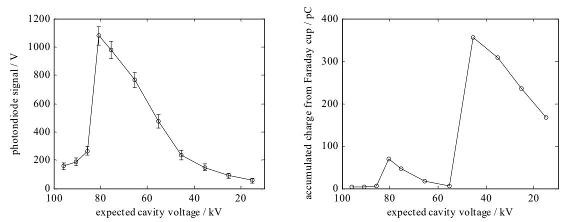

Figure 6: Signals of photodiode and faraday cup in the procedures of voltage reduction

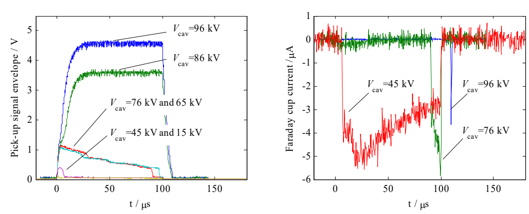

Figure 7: Waveforms of cavity voltage and Faraday cup signal at different expected voltages.

We can explain the middle state on the following assumption. In the beginning of filling process, there were enough high-energy electrons which had quite high ability of ionization. Some phase-delayed electrons produced by ionization would impact the electrode with low energy and create secondary electrons with average SEY above unity. The hysteresis of phase and energy of ionization electrons would create a new pattern of multipactor and that may expend the multipactor zone.

This assumption can also explain the asymmetry due to active detuning shown in Fig. 8. The asymmetry observed in experiments were more obvious than that in simulation. When the voltage reached a high value with a certain detuning, the deviation between voltage and driving current of power source was large enough to intensify or mitigate the multipactor.

When we increased the gap width, we could get a wider middle zone between 1st and 2nd threshold voltage, shown in Fig. 8. The lower boundaries, also defined as 2nd threshold voltage, were found increased with the gap width. We can increase the δ_m in simulation to make the agreement with experiment results, listed in Table 1. The possibility of ionization increased with the increment of gap width, and we could get a narrow existence zone for ionization with a small gap.

Table 1: Measured Second Threshold Voltages

Parameters	2nd Threshold Voltage /kV	Fitted δ_m
L_{gap}=50 mm, Q_L=1290	14.1	1.50
L_{gap}=100 mm, Q_L=1280	24.1	1.88
L_{gap}=150 mm, Q_L=1387	32.6	2.21
L_{gap}=150 mm, Q_L=1960	52.6	2.26
L_{gap}=150 mm, Q_L=830	17.7	2.06

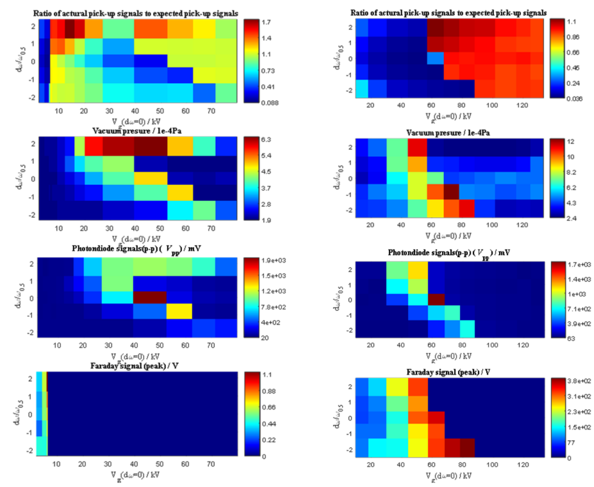

Figure 8: Signals with different detuning frequencies, expected voltages and gap width (left: 50 mm, right: 100 mm).

CONCLUSION

In high-Q systems, Beam loading is the main reason for the limitation of the development of multipactor. Phase-shifting of electric field due to transient beam loading and sequent deviation of resonance condition cause the break of multipactor. This results in failure of RF field construction with certain predicted voltage. Threshold voltage could be a key indicator of multipactor zone in a pulsed RF system. Due to the ionization in background gas, the voltage threshold range is enlarged. The hysteresis of phase and energy of ionization electrons would be a new driving factor for the growth of multipactor and subsequently expand the multipactor zone.

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