Dependence of the Multipactor Saturation Current on the RF Frequency

Hyun-Jong You,* Yong-Ho Jung and Kyu-Sun Chung

Department of Nuclear Engineering, Hanyang University, Seoul 133-791

Bong-Guen Hong

Nuclear Fusion Laboratory, Nuclear Physico-Engineering Team,
Korea Atomic Energy Research Institute, Taejon 305-600

(Received 14 September 2001, in final form 26 February 2002)

The multipactor saturation current (MSC) has been measured for RF frequencies to address limitations on the theoretical prediction. The dependence of the MSC on the RF frequency is studied by measuring the MSC in a multipactor simulator, which consist of two parallel 70-mm-diameter copper electrodes by changing the frequency from 25 to 43 MHz. The measured saturation current has the same order as the theoretical prediction of Vaughan, but the measured MSC has a higher rate of increase than Vaughan’s formula, \( I_S \sim f^3 \). When the measured MSC is shown on a log-log plot, it is not linear for all frequencies. Only in the relatively higher frequency range (>30 MHz) is its dependence linear. In that range, the MSC can be fitted as \( I_S \sim f^{3.5} \). These differences are explained from the viewpoint of saturation mechanisms, where both impact phase-dependent phase error and nonzero electron initial velocity are considered.

PACS numbers: 50
Keywords: Multipactor, Saturation current

I. INTRODUCTION

A multipactor is a resonant discharge produced by an RF field in which an explosive growth (avalanche) in the electron population can occur via secondary emission driven by the RF field [1]. The discharge can take place over a wide range of frequencies from the MHz range to tens of GHz and in a wide array of geometries. The discharge has been frequently observed in high frequency and high vacuum systems, such as RF windows, cavities, accelerator structures, microwave tubes and devices, and ion cyclotron resonance heating (ICRH) antennae and their transmission lines in nuclear fusion devices.

Specially, the multipactor and its transition can cause severe problems in an ICRH antenna or in vacuum transmission lines where a multipactor leads to a pressure increase in the vacuum components and ultimately yields a forbidden band of launching power [2]; Gas desorption due to the multipactor is a main cause of electric breakdown, causing a multipacting arc [3]. In contrast to the first two effects, a low power multipactor discharge can be used as a surface conditioning method to remove absorbed gas. In high power operation, in which multipactor discharge is not considered to be possible, a multipactor discharge can occur in the ramp-up phase of RF pulses or in the neighborhood of antenna short circuits [4]. However, many experiments have concentrated on high power launching to an ICRH antenna and on its suppression.

A multipactor was first observed in 1924 by the Guttons [5] and was first identified and studied by Farnsworth [6]. Experiments in the 1930s and theories in the 1940s led to the resonant condition on the transit time for electrons emitted with zero initial velocity, which was derived by Henneburg et al. With Gill and Engel in the 1940s, Hatch and Williams systematically studied the multipactor and reformulated the theory to explain their experiments in the 1950s [7,8]. Also, they outlined the region susceptible to multipactor, both experimentally and theoretically. Vaughan has given an excellent discussion and analysis for the magnetic field free case, particularly adressing phase focusing effects and multipactor saturation mechanisms. Riyopoulos et al. extended this to include a crossed-magnetic field [9]. Recently, it was reported that sufficient amounts of gas can be produced by the multipactor due to electron stimulated and thermal desorption from the conducting walls and that the multipactor can reach the transition region [10].

However, despite these significant results, there are several problems awaiting solution. Specially, for the MSC and its evolution time, current theories are still trying to explain the saturation mechanism and do for either the MSC or the evolution time. The level and the

*E-mail: factorial@hanyang.ac.kr
evolution time of the multipactor current are very important parameters that determine how much power is dissipated parasitically and whether the voltage breaks through the multipactor susceptible region, respectively. In 1988, Vaughan derived a semi-quantitative expression for the multipactor current to each electrode in a parallel geometry with no magnetic field. His formula was based on the balance between the gain of electrons by phase focusing and the loss by the phase dispersing effect of space charge force. However, his formula included some assumptions that the available resonant phases were within the range 0 to 32.5° and that phase errors due to the space charge were constant and independent of the impact phases. Therefore, Vaughan himself considered his theory as being a semi-quantitative theory, with a better than order-of-magnitude experimental support, but by no means complete. In addition, it has recently been shown that the small, 1 eV or less, kinetic energy of the emitted secondaries suffices to overcome opposing ac electric fields at the moment of emission; thus the resonant impact phases can be negative [11]. It was also shown that the space-charge-induced phase error also depended on the impact phase [12]. Looking into these recent results, we expect that there must be some differences between Vaughan’s formula and the real multipactor current.

From these points of view, the measurement of the MSC level as a function of the applied frequency can be a starting point for verifying the limitations of the theoretical prediction. The MSC is measured and its frequency dependence mainly studied to understand and simulate these differences in the region of a few tens of frequencies.

This paper is organized as follows: The experimental setup and diagnostics are addressed in section II. Section III covers experimental methods and results. Conclusions are given in the final section.

II. EXPERIMENT

1. Experimental Setup

The RF signal is modulated with a triangular pulse and is amplified by using an RF amplifier capable of producing an output power of more than 150 W. For impedance matching, a two-capacitor tuner is inserted between the amplifier and the electrodes. The tuner is adjusted so that a minimal reflected power is measured with the directional coupler when there is no multipactor discharge. The discharge chamber is pumped to a base pressure of less than 1×10^{-7} mbar through its bottom port. A schematic view of the experimental setup and a detailed view of discharge chamber assembly are shown in Fig. 1. The discharge chamber consists of two 70-mm-diameter copper electrodes mounted parallel to each other at a distance of 42 mm. A voltage-current probe and a voltage coupler are used to measure the RF voltage between the electrodes. The pressure variation, light emission, multipactor current and RF transmission are monitored with a cold cathode gauge, photo multiplier tube (PMT), electron collector (mounted on the ground electrode), and directional coupler, respectively.

2. Diagnostics

The voltage-current probe (V-I probe) and the electron collector have been designed and calibrated to measure the RF voltage and the RF current. In addition, the PMT is mounted on the side port of the chamber, and the directional coupler is inserted between the power amplifier and the tuner. The designed voltage-current probe and its equivalent circuit are shown in Fig. 2. This probe is for measuring the voltage between the electrodes. Compared to the wavelength of about 10 m, the distance between the probe and the electrodes is so small that the voltage difference between the two is negligible. This probe is also used to observe the variation of the load impedance due to the multipactor. A simple analysis of the equivalent circuit of Fig. 2(b) yields

\[ r_V = \frac{|V_{R1}|}{V_1} \approx C \omega, \quad \text{when} \quad R_1 \ll \frac{1}{\omega C} \]  

(1)

\[ r_I = \frac{|V_{R2}|}{I_1} \approx \frac{M}{2} \omega, \]  

(2)
where $\omega$ corresponds to the angular frequency of the RF field. $r_V$ is the ratio of the voltage $V_1$ on the inner line to the voltage $V_{R1}$ across the resistor $R_1$. This method of measuring the voltage is to take advantage of the capacitance $C$ between $A$ and $B$ in Fig. 2. $r_I$ is the ratio of the current $I_1$ on the inner line to the voltage $V_{R2}(= I_2 R_2)$ induced on a small single loop by magnetic induction. The probe characteristic is calibrated by using a network analyzer. As shown Fig. 3, the calibrated result shows that both $r_V$ and $r_I$ are linearly proportional to the frequency within the range of tens of MHz. The values of the RF voltage and the current are accurate to within $\sim \pm 5$ percent.

A cone-shaped carbon collector has been made and is used for measuring the RF current. Its design is shown in Fig. 4(a), and its schematic circuit including the pico-ammeter circuit is shown in Fig. 4(b). The growing number of electrons due to secondary electron emission is drawn to the carbon collector through the hole on the ground electrode.

There are three effects which can cause serious current loss and gain in this collector system. First, large-incidence electron loss in the collimator will be negligible because the incident angle of the electrons is about normal in our system which has no magnetic field. Second, electron scattering through the collimator edge is estimated to give $\sim 20\%$ loss of the collimated current for $\alpha = 2$, where $\alpha$ is the ratio of the collimator length to the collimator diameter. The third effect is the secondary and reflected primary electrons emitted from the collector itself. In order to suppress this effect, the collector is made with carbon (soot) with $\delta = 0.45$ and is shaped like a cone. Since secondary electrons are emitted in a cosine distribution about the surface normal, the cone shape of the collector directs most of the secondaries back toward the collector [13–17]. A 50 ohm cable is then connected at the back of the collector.
cable propagates the signal to an oscilloscope or a picoammeter (KEITHLEY 480). The cable length of 30 cm is short enough to respond to the current variation simultaneously for frequencies of tens of MHz.

III. RESULTS

To see the dependence of the collector current on the RF frequency $f$, we applied a 2 Hz triangularly modulated RF voltage is applied to the electrode. Since the multipactor saturation current critically depends on the electrode surface conditions, the electrode surfaces need to be stabilized before the measurements are made. This stability condition is achieved by operating the multipactor discharge for more than 10 minutes, but this still will give $\sim +3$ percent uncertainty in the collector signal [2]. In Fig. 5 the collector current $I_S$ is measured by using the electron collector and the RF voltage amplitude $V_{RF}$ by using a V-I probe. We can observe the dependence of the susceptibility and MSC on the frequencies. The susceptibility range becomes broad (horizontal axis) and the saturation current increases (vertical axis) more and more as the frequency increases. The current maximum for each frequency is picked out of the data in Fig. 5, and in Fig. 6(a) the current maxima are plotted together with the theoretical values as a function of frequency. The theoretical values of the saturation current $I_S$ were calculated by using Vaughan’s formula [1, p. 1178]:

$$I_S = \frac{\omega}{2\pi} \sigma_{\text{max}} A,$$

where

$$\sigma_{\text{max}} = a \tan \left( \frac{1}{N\pi} \right) \frac{2m}{e} \frac{\omega^2 d}{\pi^2} \frac{2 \cos \alpha N \pi \sin \alpha}{N \pi \cos \alpha + 2 \sin \alpha}$$

$$= 0.3303 m \frac{\omega^2 d}{e_0 \pi^2}, \text{ at } N = 1, \alpha = 0.5 a \tan \frac{2}{\pi}$$

with $\sigma_{\text{max}} [\text{C/m}^2]$ being the maximum of the charge density, $A$ the electrode area, $d$ the gap distance, and $\alpha$ the resonant electron impact phase. This equation says that the multipactor current is proportional to $f^3$. We can see in Fig. 6(a) that the measured data have the same order as the theoretical values, but that their frequency dependence is not exactly in agreement with theoretical values. As seen in Fig. 6(b), which is a logarithmic plot of Fig. 6(a), the measured data do not show a linear dependence for all frequencies, in contrast the theoretical values; the measured data become nonlinear as the frequency approaches the lower frequencies ($\leq 30$ MHz). For relatively higher frequencies ($> 30$ MHz), the dependence becomes linear and then can be fitted as $\sim f^{3.5}$.

In order to examine these differences we need to map the susceptibility curve from both the measured data and the theoretical calculation. Figure 7 illustrates the lower and the upper boundaries of the multipactor region vs. frequency. The data in Fig. 5 are used for mapping the measured susceptibility curve. The dotted lines represent resonant conditions at the indicated phase
Fig. 7. Log-log plot to illustrate the theoretical calculation and the measured values for multipactor susceptible region. The dotted lines represent resonant conditions at the indicated phase angles. The heavy curve represents the lower boundary of the theoretical susceptible region limited by an impact voltage of 200 V. The multipactor current reaches its maximum at a different resonant phase between \(-30^\circ\) and \(-50^\circ\).

angles. The heavy curve represents the lower boundary of the theoretical susceptibility region, which is limited by the impact voltage of 200 V. The theoretical values are calculated under the following conditions: first, the initial emission energy of secondary electrons is \(\sim 5\) eV; second, the first crossover energy of the copper electrode is 200 eV [18]. The first condition can make the multipactor persist for a resonant phase as negative as \(-50^\circ\). It is shown in Fig. 7 that the lower boundary is approximately determined by not resonant phase limit but by the impact energy limit, which is the second condition. The impact voltage of electrons with phases such as \(-15^\circ\), \(0^\circ\), \(15^\circ\) and \(32.5^\circ\) can not reach the first crossover energy of 200 eV. Though the agreement between the experimental and the theoretical susceptibility curves is not very good, there are some important points that can be discovered in Fig. 7: the multipactor resonant phases are in as deep as near \(-40^\circ\), and the impact phases corresponding to the current maximum are not constant but change with the frequency.

Now, we can return to the Fig. 6. According to the previous paragraph, the differences between the two MSC values can be attributed to Vaughan’s inadequate assumptions in his formula. First, as mentioned in Section I, Vaughan considered the phase error due to mutual repulsion of the space charge force as being a constant value by fixing the resonant phase \(\alpha\) as 0.5 atan\((2/N\pi)\). However, the space charge force is not constant, but depends on the resonant impact phase \(\alpha\). Second, the multipactor with nonzero initial velocities will be pushed toward negative resonant phases by the following scaling \(\phi_c \cong \sqrt{2mdv_0/eV_{RF}}\), where \(\phi_c\) is the critical negative impact phase and \(v_0\) is the electron initial velocity [11]. Lastly, having little connection with the previous paragraph, the large difference at relatively low frequencies (\(\leq 30\) MHz) may be due to a transition effect as being the dominant process between the impact energy limit and the resonant phase limit in the neighborhood of the cutoff frequency. The cutoff frequency means the limit of the frequency for which the multipactor extinguishes [2]. Near the cutoff frequency, the multipactor actually experiences a gradual transition between the energy (impact voltage) limitation and the phase angle limitation as the dominant process, whereas the simple current theories, such as Vaughan’s theory, show an abrupt transition. As a result, the Eq. (3) can not be applied to the multipactor phenomenon near the cutoff region because the saturation mechanism correspondingly will have a more complicated form.

A closer examination of the previous three reasons for the differences needs more exact calculations: the first reason requires a calculation with a phase dependent space charge force, which is not simple. The second reason must be verified by using the phase focusing effect near all resonant phases, including negative resonant phases. The third reason also must be carefully examined as the transition process between the phase limit and the energy limit under the exact surface condition.

IV. CONCLUSIONS

To study the dependence of the multipactor saturation current on the RF frequency and to investigate the limitations of the current theory, we measured the MSC and compared the results with the theoretical values as a function of frequency from 25 to 43 MHz. The measured MSC is not in good agreement with Vaughan’s prediction, \(I_S \sim f^3\); at relatively high frequencies (\(\geq 30\) MHz), the measured MSC can be empirically fitted as \(I_S \sim f^{3.5}\), and its dependence becomes much different in the neighborhood of the cutoff frequency. These gaps can be expected to become narrower by considering the following: a) the phase error due to the space charge force depends on the resonant impact phase, b) the impact phases corresponding to the current maximum are not constant, but are a function of frequency, and c) the saturation mechanism near the cutoff frequency appears to be more complicated than that of the simple current theories. More detailed calculations considering these modifications will be addressed in the near future.

ACKNOWLEDGMENTS

This paper was supported by Korea Atomic Energy Research Institute. The authors acknowledge discussions with Yong-Dug Bae, Churl-Kew Hwang and Sun-Jeong Wang.
REFERENCES