# DYNAMICS OF MULTIPACTING IN RECTANGULAR COUPLER WAVEGUIDES AND SUPPRESSION METHODS *

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*Abstract*

Two methods can be used to suppress multipacting in a rectangular coupler waveguide. The slotted waveguide method calls for opening slots on the broad walls in the wave propagation direction that perturb the resonance and trap multipacting electrons. The DC magnetic bias method utilizes a solenoid coil wrapped around the waveguide to generate a mild DC magnetic field in the waveguide space that bends the trajectory of multipacting electrons. Electron stimulated desorption plays a critical role in the dynamics of multipacting induced breakdown. Ionization discharge of desorbed gases is the direct cause for RF breakdown. Adequate pumping for the coupler waveguide is essential for a smooth operation.

## INTRODUCTION

Higher order two-sided multipacting between the broad walls of a rectangular coupler waveguide is among the leading mechanisms inducing RF breakdown in today's multi hundred kW waveguide couplers for SRF cavities [1][2]. The RF processing technique was so far the only method to alleviate the problem to some extent. However, this method is time consuming and its effectiveness is greatly reduced at high RF power levels for which the impact energy of multipacting electrons is higher than 500 eV. The lack of effective method for multipacting suppression has prevented a rectangular waveguide coupler from reaching its intrinsic high power capability.

Multipacting induced breakdown also occurs in coaxial coupler waveguides. In this case, only the outer conductor is involved in the dominant multipacting zones [3]. The DC electric bias method has been developed to actively suppress multipacting in coaxial waveguides [4]. This method of multipacting suppression proved to be very effective and helped to overcome multipacting in coaxial couplers and to achieve very high power levels. This as well as somewhat better understanding of multipacting phenomenon in coaxial lines is one of the reasons why coaxial waveguide couplers are often preferred to rectangular waveguide couplers.

The power required to be delivered by RF couplers has been steadily increasing. Some applications call for running rectangular waveguide couplers of existing design at an extremely low trip rate due to RF breakdown. Some frontier machines require significantly higher power (CW) than what can be provided by the state-of-the-art coaxial couplers operating in the same class. In case the power limit of a coaxial coupler waveguide is reached, a rectangular waveguide coupler will have to be considered. Effective methods to suppress multipacting in rectangular coupler waveguides are thus needed to warrant smooth coupler operation and higher power delivery.

## WAVEGUIDE MULTIPACTING EXPERIMENTS

Experimental studies of multipacting in CESR type rectangular coupler waveguides were conducted. The layout of the experiment is shown in Fig. 1 schematically. Detailed description of the apparatus can be found in Ref. [5]. The waveguide cross section is 18 inches by 4 inches. The regular waveguide was used to establish the reference multipacting and was also used to study the DC magnetic bias method. To test the slotted waveguide method, another waveguide featured a groove in one of its broad wall. Diagnostics include electron probes at various locations, an electron energy analyzer, a photo-multiplier tube (PMT), and a cold cathode gauge. Waveguides were tested in traveling wave, partial reflected wave, and standing wave modes. In traveling wave mode, tests were conducted up to a power of 500 kW with 2 ms long RF pulses and a duty factor of 10%.

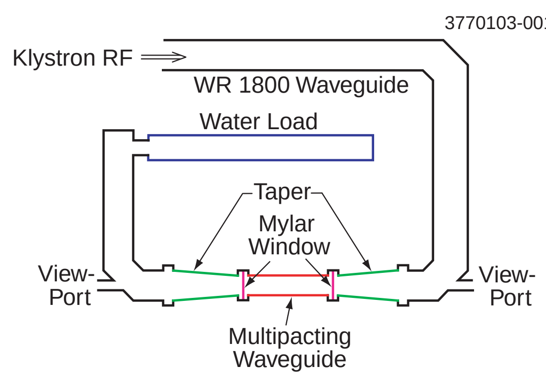


Figure 1: Layout of the rectangular waveguide multipacting experiment.

## DYNAMICS OF MULTIPACTING INDUCED BREAKDOWN

By definition, multipacting is a resonant multiplication process in which the number of electrons grows exponen-

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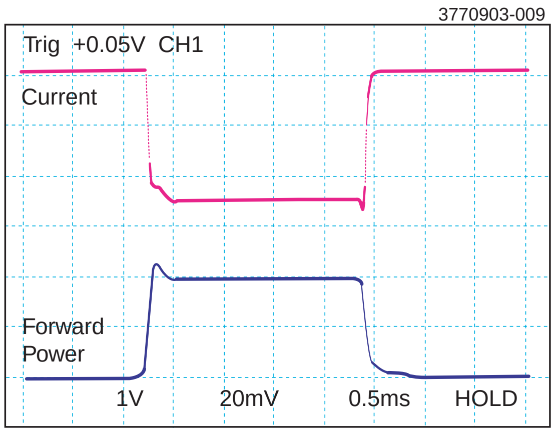


Figure 2: Multipacting current is saturated on a $ms$ time scale. Lower trace: forward power; Upper trace: multipacting current.

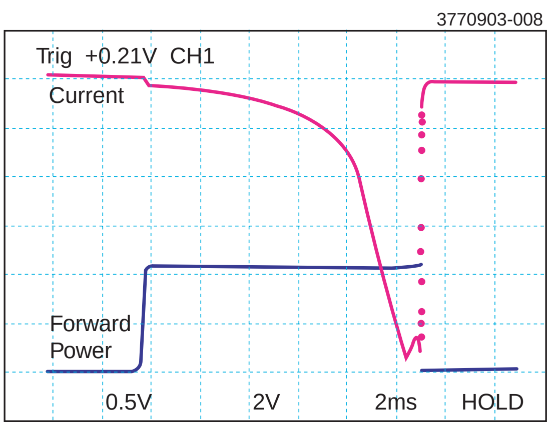


Figure 3: Growing multipacting current for long pulse lengths. Lower trace: forward power; Upper trace: electron current.

tially. For the two-sided higher order multipacting discussed in this paper, a multiplication factor of 1 billion would be reached in less than 1 $\mu s$. This type of fast electron avalanche is however not observed in the experiments. Instead, as shown in Fig. 2, a leveled multipacting current is detected on the time scale of $ms$, during which no reflected RF power is measured. The saturation of multipacting current is most likely due to the space charge effect.

When the length of the RF pulse is increased, the detected electron current exhibits a slow growth followed by a fast growth. Fig. 3 shows the electron current when the RF has a pulse length of $\sim 10\ ms$. A whitish-blue light accompanies the electron current. The light intensity increases as the current growing. Eventually this light reaches high enough an intensity level to trip off RF due to an excessive PMT current. Immediately before the RF is tripped off, some reflected power is detected, indicating a significant change of the waveguide impedance by the electronic activity.

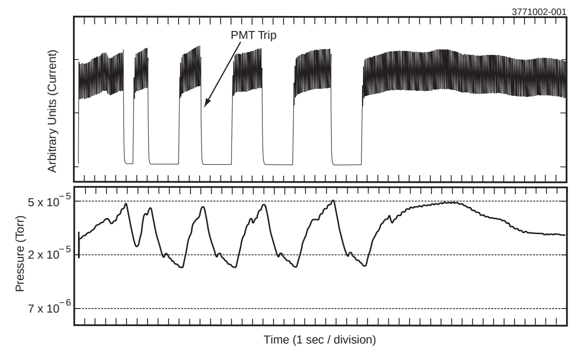


Figure 4: Correlation between the probe current and the waveguide pressure.

A growing current for a long pulse length is due to added electrons originated presumably from ionization discharge of gas molecules resulted from electron stimulated desorption (ESD). Calculations show that the impact energy of multipacting electrons is in the range 140 eV - 900 eV for a forward power of up to 500 kW. Clearly, multipacting electrons have a high ESD yield. Fig. 4 depicts the correlation between the probe current and the pressure in the test waveguide for a given RF power level when an active pumping of the waveguide space is maintained. Upon turning on the RF power, the waveguide pressure starts to go up slowly until the RF is tripped off by the PMT light. Then the pressure recovers until the RF is turned back on by the control system, when the pressure goes up again and the cycle is repeated. Each time RF stays on longer than during previous cycle and finally after a few cycles the RF stays on without tripping and the pressure in the waveguide goes down. This pattern is repeatedly seen each time the power level is increased. After the 500 kW level is reached, the RF power is ramped down. In this case, the waveguide vacuum remains stable although a current can still be detected by electron probes. The above described process is essentially RF processing. Based on these findings, the following conclusions can be drawn: (1) RF processing drives out gases from the waveguide surface layer through ESD by multipacting electrons; (2) The direct cause for RF breakdown is ionization discharge of desorbed gas molecules; (3) The residual persisting multipacting after RF processing is harmless.

The measured electron energy spectrums show that a large number of detected electrons have an energy of less than 100 eV, which is consistent with the energy for a large ionization cross section. Fig. 5 shows the spectrum for a forward power of 250 kW in traveling wave mode. The end-point energy of the spectrum is 470 eV, consistent with the impacting energy of multipacting electrons predicted by simulations with the code Xing [2].

The low energy constituent below the 60 eV turning-point can be attributed to ionization discharge. Simple analytical calculations show that at 250 kW power level an electron generated at 0 degree phase angle exhibits an oscil-

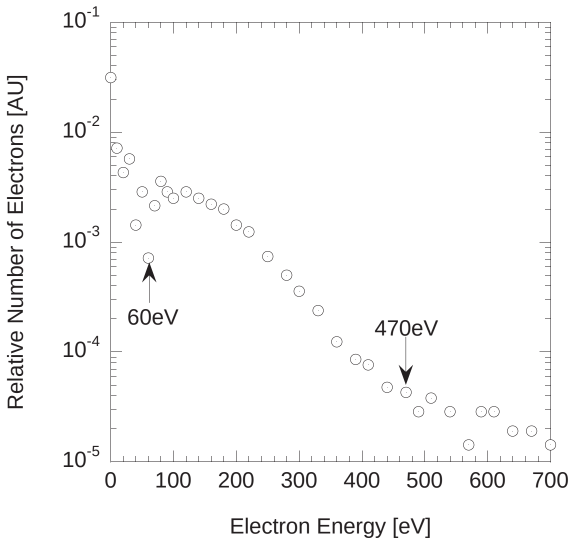


Figure 5: Electron energy spectrum for a forward power of 250 kW.

lation movement within the waveguide space and its energy is modulated with an amplitude of 100 eV, which is qualitatively consistent with the measured turning-point energy.

## MULTIPACTING SUPPRESSION METHODS

Both the slotted waveguide method and the DC magnetic bias method show multipacting suppression effect. For the slotted waveguide featured with one slot (5 mm wide by 5 - 10 mm deep) along the center line of a broad wall, multipacting current is reduced by a factor of 2 - 7 for the power range of 0 - 500 kW in traveling wave mode. Observation and imaging of activities inside the waveguide space was made through view ports installed on the E-bends located on both sides of the test waveguide. In the waveguide space corresponding to the slot, a dark region is visible against the whitish-blue background, which is due to discharge of gas molecules desorbed by multipacting electrons. This observation not only confirms the multipacting suppression effect of the slot, but also reveals that multipacting develops across broad walls over almost the entire width of the waveguide. It is thus concluded that, to achieve a complete multipacting suppression with the slotted waveguide method, multiple slots are needed on both broad walls.

Complete multipacting suppression is realized with the DC magnetic bias method. This is shown in Fig. 6. The needed bias field to fully suppress multipacting, $B_s$, in a rectangular waveguide operated in traveling wave mode has been derived,

$$B_s = 4\sqrt{\frac{\mu_0 P_f}{k\omega a b^3}}, \qquad (1)$$

where $P_f$ is the forward power, $k$ the wave propagation constant, $\mu_0$ the permeability of vacuum, $\omega$ the angular RF frequency, and $a$ and $b$ the wide and narrow dimension of

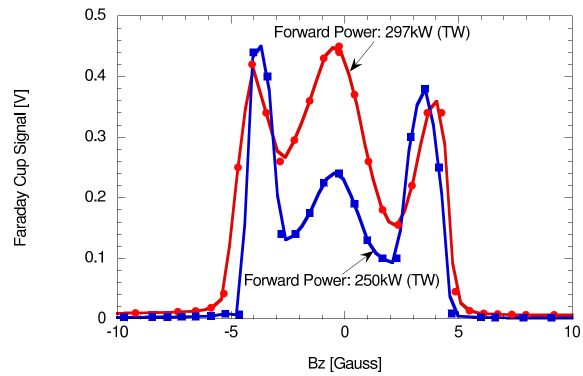


Figure 6: Multipacting suppression by the DC magnetic bias method.

the waveguide respectively. Eq. 1 is well supported by the data obtained in the presented studies.

An interesting effect of multipacting enhancement is observed for a bias field smaller than the suppression field. This is due to glance incidence of multipacting electrons. The enhancement effect was also observed when the waveguide is operated in standing wave mode. This effect can be used to promote multipacting during RF processing of waveguide couplers.

## DISCUSSION

As we have seen, the direct cause of RF breakdown is ionization discharge of desorbed gases due to multipacting electrons. When the stored gases in the waveguide surface layer is exhausted by RF processing, RF breakdown will not occur despite the persistence of multipacting. It is thus justified that off-situ bake out of coupler components will reduced the RF processing time.

Some RF coupler components for SRF cavities are at cryogenic temperatures. Residual gases are cryo-sorbed on the surfaces of these components. Ceramic RF windows usually need to be conditioned in-situ, during which gases are driven out of ceramic. Condensables such as water vapor, carbon dioxide and carbon monoxide are to be cryosorbed on the cold coupler surfaces if not pumped out by vacuum pumps [6]. As a result, the cold coupler surfaces are always covered with many monolayers of gas molecules. These condensables when released by ESD of multipacting electrons will cause ionization discharge and RF breakdown. It is thus essential to obtain adequate external pumping speed to quickly remove gas molecules and maintain a low pressure in the coupler waveguide space to avoid multipacting induced breakdown. This practice is particularly necessary for couplers operated in CW mode.

It is anticipated that the DC magnetic bias method can be also applied to coaxial coupler waveguides, because a solenoid magnetic field provides similar trajectory bending for multipacting electrons of the one-sided outer conductor multipacting. The DC electric bias method, although proven effective in suppressing multipacting in coaxial coupler waveguide, has the disadvantage of using thin dielectric films which deteriorate over time and cause failures when the DC bias voltage is applied. In contrast, the DC magnetic bias method warrants a better long term reliability. Another advantage of the DC magnetic bias method is that coupler waveguide segments having different dimensions can be fitted with different solenoid coils, each proving an optimal biasing field. Whereas for the DC electric bias method, one bias voltage is applied indiscriminately on the center conductor of coupler waveguides.

## CONCLUSION

Two methods are found to suppress multipacting in rectangular coupler waveguides, namely the passive slotted waveguide method and the active DC magnetic bias method. The DC magnetic bias method is anticipated to be equally applicable to coaxial coupler waveguides. Ionization discharge of gas molecules due to ESD by multipacting electrons is the direct cause for RF breakdown. It is essential to have adequate external pumping speed for coupler waveguides, particularly for CW and long pulse applications.

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