Defence Science Journal, Vol. 71, No. 3, May 2021, pp. 337-340, DOI : 10.14429/dsj.71.16769

Multipaction Susceptibility Margins in Space Travelling-wave Tubes

Talur Chanakya*, N.K. Manker, V.B. Naidu, and S.K. Datta

DRDO-Microwave Tube Research & Development Centre, Bengaluru - 560 013, India
**E-mail: chanakyaiith@gmail.com*

ABSTRACT

Study of multipaction breakdown margins in the output connector of a travelling-wave tube (TWT) is essential for application in satellite-borne systems. A TWT uses a coaxial ceramic window, a coaxial output coupler and / or a waveguide output coupler that are prone to multipaction breakdown boosted by high RF power due to the ion accumulation in critical regions during the transition of the satellite through plasma pockets in space. A detailed procedure for estimating the multipaction susceptibility margins in a TWT using CST studio and analytical equations is presented in this paper, and output couplers of two typical TWTs are analysed and the results are presented.

Keywords: Multipaction breakdown; Space TWT; Coaxial coupler; Waveguide coupler

NOMENCLATURE

d	Gap between the surfaces
f	Operating frequency
F	Voltage magnification factor
fd	Frequency-gap product
P_{th}	Power margin for multipaction
V_i	Voltage corresponding to RF power flow of 0.5 W
V_0	Voltage corresponding to rated RF power flow
V_{th}	Threshold voltage for multipaction to occur

1. INTRODUCTION

Multipaction breakdown is a phenomenon where a cloud of secondary electrons build-up exponentially between metal surfaces due to electronic acceleration in synchronism with alternating RF fields leading to a high frequency discharge under optimum conditions[1-3]. Multipaction can cause temporary damage or even permanent damage to the propagating structures depending on its severity. In a travelling-wave tube (TWT)[4], the output coupler is the most susceptible unit for multipaction breakdown. The amplified RF output in a TWT is extracted either through a coaxial or waveguide coupler depending on the power levels and applications. The output coupler in a TWT is an impedance matching circuit that matches the impedance of the RF interaction circuit with that of the output connector (coaxial or waveguide type) through a coaxial ceramic window. It is sometimes possible that some of the stray electrons from the electron beam travel towards the coupler or the ions get accumulated on the metal parts during the transition of a satellite through Van-Allen radiation belts. These electrons or ions can grow exponentially when high power RF flows through the coupler leading to multipaction breakdown.

Received : 02 February 2021, Revised : 12 February 2021
Accepted : 18 February 2021, Online published : 17 May 2021

Multipaction depends on many factors like vacuum level, frequency-gap product, surface properties like secondary electron emission yield, initial electron energy, phase between RF field and electron emission, RF power level, etc. The analytical equations for multipaction in parallel plate geometry are derived and experimentally validated and are well documented in the literature[5-7]. Similarly, the multipaction threshold voltages for coaxial transmission lines are derived experimentally by Woo[8-10]. This paper presents a detailed procedure for estimating the multipaction susceptibility margins in co-axial and waveguide transmission lines using CST Studio[11] and published de-rating curves. Using this approach, multipaction margins for output couplers of two typical space TWTs operating in X- and Ku-bands with 350W of power are calculated and ascertained against space-standard issued by the European Cooperation for Space Standardisation (ECSS)[12] for the safe operation of TWTs.

2. CO-AXIAL TRANSMISSION LINE

The multipaction threshold voltages for coaxial transmission lines with varying characteristic impedances are studied and experimentally verified by Richard Woo[10] and the threshold voltage curves are generated. These threshold voltage curves are known as "Woo curves" and describe the minimum voltage required for multipaction to occur in a circuit for a given frequency-gap product. The tolerable margin in the design of a coaxial line for susceptibility to multipaction breakdown is estimated with the help of this plot (Fig. 2 in Woo[10]) coupled with 3D electromagnetic analysis of the transmission line in time domain. The detailed procedure to estimate the multipaction margins in the coaxial line is as follows:

(1) Model the transmission line in CST Microwave Studio with ports defined at both ends.

(2) Define the excitation signal corresponding to operating frequencies.
(3) Define the voltage monitors at the desired planes and measure the voltages (V_i) corresponding to RF power flow through the transmission line using time domain solver.
(4) Obtain the voltage (V_0) corresponding to the rated RF power handling of the circuit using the relation that power is proportional to the square of voltage.
(5) Calculate the frequency-gap products (*fd*) at these planes and estimate the threshold voltage (V_{th}) required for multipaction to initiate using the corresponding impedance curve of Richard Woo (Fig. 2 therein)[10]. If the curve for the exact impedance is not found, consider the lower impedance curve and calculate the threshold voltages. For a given frequency-gap product, the threshold voltage increases with an increase in impedance. Considering a lower value of impedance would be thus providing a safer margin.
(6) The power margin is calculated using the following relation as

$$P_{th}(dB) = 20\log_{10}(V_{th}/V_0)$$

(7) Compare this margin with the space guidelines for multipaction[10] of Type 1 classification (maximum 8 dB for RF paths that are entirely metallic).

3. WAVEGUIDE TRANSMISSION LINE

Analytical equations for estimating the multipaction threshold voltages for the parallel plate geometry using different approaches are also well documented in the literature. The threshold voltage mainly depends on the electrode material properties. The experimentally validated nomograms for estimating the multipaction threshold voltage in parallel plates for typically used materials for space applications are published by the European Cooperation for Space Standardisation (ECSS) in a standard document[12]. These nomograms (Fig. 5-1 of the ECSS Standard[12]) describe the peak voltage required for the multipaction to occur for a given frequency-gap product in parallel plate geometry. In order to estimate the multipaction voltages in waveguides, one needs to start by considering them as parallel plate geometry and find out the critical voltage. Then the voltage magnification factor due to fringing fields is calculated based on the length-to-gap ratio as given in Wolk[13], *et al.* (Fig. 2 therein). The procedure to estimate the multipaction margins in the waveguide is as follows:

(1) Model the transmission line in CST Microwave Studio with ports defined at both ends.
(2) Define the excitation signal corresponding to operating frequencies.
(3) Define the voltage monitors at the desired planes and measure the voltages (V_i) corresponding to RF power flow through the transmission line using time domain solver.
(4) Obtain the voltage (V_0) corresponding to the rated RF power handling of the circuit using the relation that power is proportional to the square of voltage.
(5) Calculate the frequency-gap product at these planes and estimate the threshold voltage (V_{th}) required for multipaction to occur using the nomograms given in the ECSS Standard (Fig. 5-1 therein)[12] depending on the electrode material and the frequency-gap product.
(6) Calculate the gap-to-length ratio of the parallel plate and estimate the corresponding voltage magnification factor (F) as proposed by Wolk *et al.* (Fig. 2 therein)[13]. For gap-to-length ratio greater than 1.5, the value of F to be assigned as 7 (as F shows an increasing trend with gap-to-length ratio).
(7) The power margin is calculated using the following relation as

$$P_{th}(dB) = 20\log_{10}(V_{th} \times F / V_0)$$

(8) Compare this margin with space guidelines for multipaction[12] of Type 1 classification.

4. X-BAND AND KU-BAND TWT COUPLERS

Using the above approach, multipaction margins are calculated for the output couplers of the two different TWTs designed to operate in X-band and Ku-band delivering 350W of peak power. These couplers consist of both co-axial and waveguide transmission lines. The X-Band TWT uses WR-90 waveguide coupler while the Ku-band TWT uses WR-62 waveguide coupler, both made of aluminium (Al-6061). The couplers are modelled in CST studio and voltage monitors at different planes are defined as shown in Fig. 1. The Simulated VSWR plots for X-band and for the Ku-band Couplers are shown in Fig. 2 and Fig. 3, respectively. The simulated voltages (V_i) for the X-band and for the Ku-band couplers corresponding to a power flow of 0.5W are shown in Figs. 4 and 5, respectively. The voltage corresponding to 0.5W of RF power flow in the circuit (V_i) is obtained and subsequently the voltage corresponding to a power flow of 350W (V_0) is calculated from V_i. The frequency-gap product and its corresponding threshold voltages are calculated at a frequency of 10 GHz for the X-band TWT and that at 15 GHz for the Ku-band TWT and the values are shown in Table 1 to Table 3. The designs are found to have minimum power margin of 13 dB in the coaxial transmission line and that of 17 dB in the waveguide transmission line.

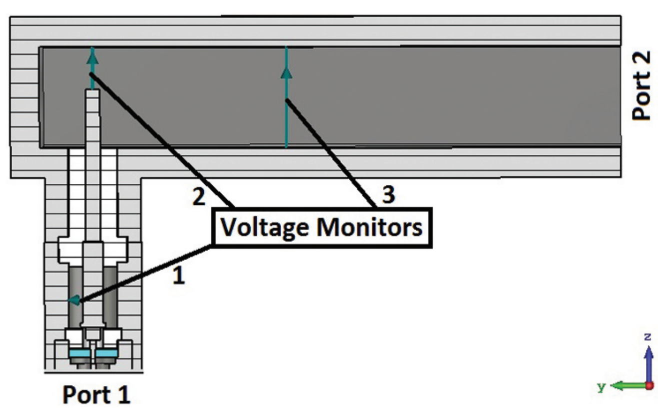

Figure 1. Typical CST model of one of the output couplers showing the voltage monitors kept at different locations.

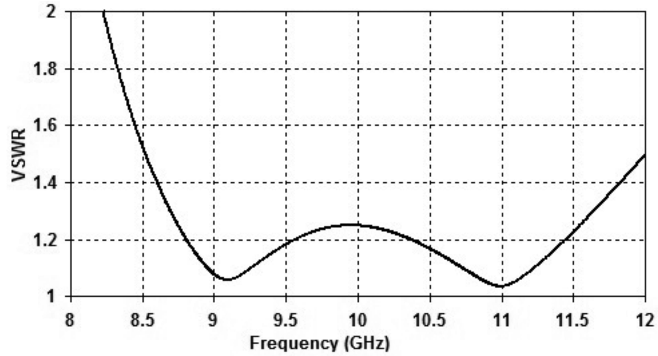

Figure 2. Simulated VSWR plot for the X-band coupler.

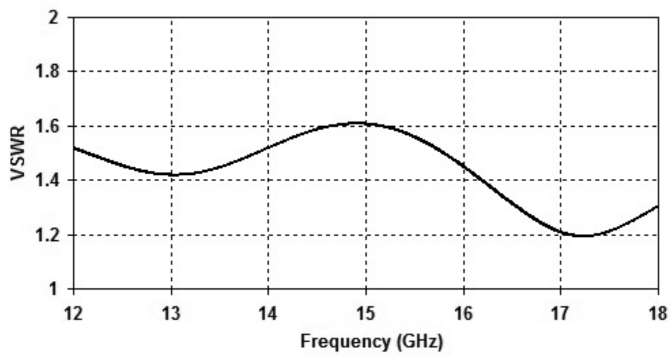

Figure 3. Simulated VSWR plot for the Ku-band coupler.

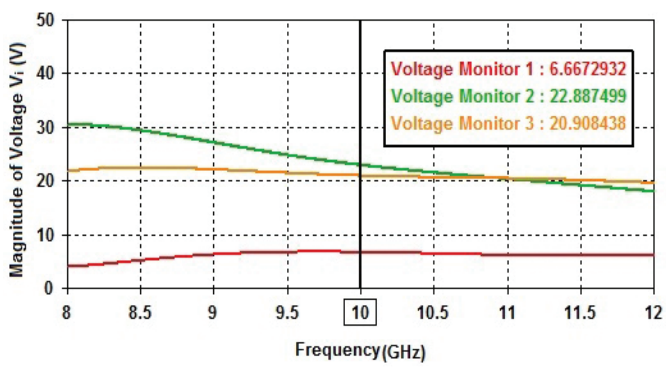

Figure 4. Voltages at different locations for the X-band coupler corresponding to an RF power flow of 0.5 W.

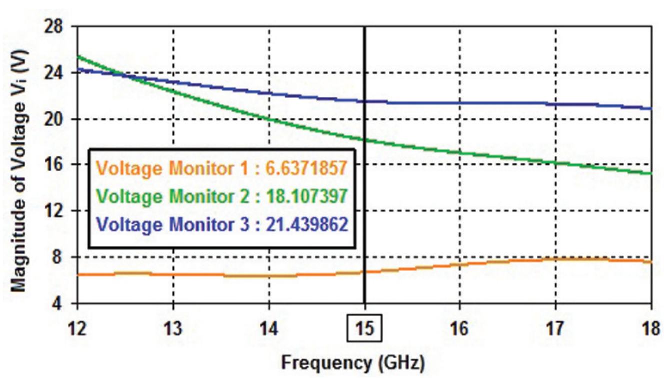

Figure 5. Voltages at different locations for the Ku-band coupler corresponding to a RF power flow of 0.5 W.

Table 1. Multipactor margin for Co-axial line

Parameter	X-Band coupler at monitor 1	Ku- Band coupler at monitor 1
Gap in cm	0.145	0.145
fd (MHz-cm)	1450	2175
V_{th} (V)	875	1284
V_i (V)	6.66	6.63
V_0(V)	176.2	175.4
Power margin (dB)	13.92	17.29

Table 2. Multipactor margin for X-band Waveguide

Monitor	2	3
Gap (*d*) in mm	4.25	10.16
Length in mm	1.50	22.86
Gap-to-length ratio	2.83	0.444
V_{th} (V)	1700	4064
V_i (V)	22.88	20.91
V_0 (V)	605	553
F	7	1
Power margin (dB)	25.88	17.32

Table 3. Multipactor margin for Ku-band Waveguide

Monitor	2	3
Gap (*d*) in mm	3.80	7.90
Length in mm	1.50	15.8
Gap-to-length ratio	2.53	0.50
V_{th} (V)	2280	4740
V_i (V)	18.10	21.44
V_0 (V)	479.0	567.2
F	7	1
Power margin (dB)	30.45	18.44

It is observed that the multipactor margin for the X-band and Ku-band couplers at location-1 (Fig. 1) is comparatively low (around 14 dB and 17 dB, respectively) against that at location-2 (around 26 dB and 30 dB, respectively). The physics attributable to this fact is that at location-1, the line is a simple free-space coaxial line for which the voltage magnification factor (*F*) is unity, whereas, at location-2, the line is a parallel plate line providing a higher voltage magnification factor of 7 for both the couplers. The high value of *F* at this location is due to large gap-height to gap-length ratio. The increased gap-height to gap-length ratio facilitates acceleration of electrons along the curved paths rather than along the straight line paths between the walls due to the fringing fields. The longer effective path lengths shift the operating location corresponding to larger values of the frequency-gap product. Higher voltage gradients across the gap are thus necessary for multipaction to occur.

5. CONCLUSION

An approach for estimating the multipaction margins for coaxial and waveguide couplers of a TWT is proposed, and the margins are calculated for two practical output couplers operating in X-band and Ku-band frequencies with peak output power of 350W. The designs are found to have minimum power margin of around 14 dB and 17 dB for output couplers of the X-band TWT and the Ku-band TWT, respectively. As per space-standards for multipaction[12], these types of output couplers should have 8 dB margins by analysis. The multipaction margins for these couplers are thus well within the limits for safe operation of the TWTs.

REFERENCES

1. Shaw, C.Z.; Silvestre, L.; Sugai, T.; Esser, B.; Mankowski, J.J.; Dickens, J.C. & Neuber, A. On the limits of multipactor in rectangular waveguides. *AIP phys. Plasma,* 2020, **27**(8), 083512. doi:10.1063/5.0012833
2. Berenguer, A.; Coves, A.; Mesa, F.; Bronchalo, E. & Gimeno, B. Analysis of multipactor effect in a partial dielectric loaded rectangular waveguide. *IEEE Trans. Plasma Sci.,* 2019, **47**(1), 259-265. doi:10.1109/TPS.2018.2880652
3. Berenguer, A.; Coves, A.; Mesa, F.; Bronchalo, E. & Gimeno, B. Multipactor analysis in circular waveguides excited by TM_{01} mode. *IEEE Trans. Electron. Devices.,* 2019, **66**(11), 4943-4951. doi:10.1109/TED.2019.2941594
4. Gilmour, A. S. Principles of Travelling Wave Tube. Artech House, USA, 1994.
5. Vaughan, J. R. M. Multipactor. *IEEE Trans. Electron Dev.*, 1988, **35**(7), 1172-1180. doi:10.1109/16.3387
6. Gallagher, W. J. The Multipactor Effect. *IEEE Trans. Nuclear Sci.*, 1979, **26(**3), 4280-4282. doi: 10.1109/TNS.1979.4330768
7. The study of multipactor breakdown in space electronic systems. Hughes Aircraft Co., Washington, NASA-CR-488, July 1966.
8. Woo, R. & Ishimaru. A. A similarity principle for multipacing discharges. *J. Appl. Physics.*, 1967, **38**(3), 5240-5244. doi:10.1063/1.1709307
9. Woo, R. Multipacting discharges between coaxial electrodes. *J. Appl. Physics*., 1968, **39(**13), 1528-1533. doi:10.1063/1.1656390
10. Woo, R. Final report on RF voltage breakdown in coaxial transmission lines. NASA-TR-32-500, California, October 1970.
11. User Manual. CST Microwave Studio, Computer Simulation Technology, Wellesley Hills, Massachusetts, 2012.
12. Multipaction Design and Test. ECSS-E-20-01A_Rev1, European Cooperation for Space Standardization, Netherlands, March 2013.
13. Wolk, D.; Vicente, C.; Hartnagel, H. L.; Mattes, M.; Mosig, J. R. & Raboso, D. An investigation of the effects of the fringing fields on multipactor breakdown. *In* Proc. of 5th Int. Workshop on Multipactor, Corona and Passive Intermodulation in Space RF Hardware (MULCOPIM), 2005.

ACKNOWLEDGMENT

The authors are thankful to the Director, Microwave Tube Research and Development Centre (MTRDC), DRDO, India for the kind permission to publish this work.

CONTRIBUTORS

Mr Talur Chanakya received his BE in Electrical Engineering from the Indian Institute of Technology, Hyderabad, India, in 2012. He is currently working as a Scientist at DRDO-MTRDC, Bengaluru, India. His research interests include CAD and development of helix TWTs. He is a member of the Vacuum Electronic Devices and Applications Society (VEDAS).
In the current study, he has been the main person behind formulating the procedure and analytical calculations.

Mr Nilesh Kumar Manker received BE in Electronics and Communication from Rajiv Gandhi Prouyogiki Vishwavidyalaya, Bhopal and M. Tech in Microwave Electronics from University of Delhi. He is currently working as a Senior Research Fellow at DRDO-MTRDC, Bengaluru, India. His research interests include CAD of electromagnetic circuits.
In the current study, he has supported the work by carrying out the simulation work.

Mr Vemula Bhanu Naidu received the BE degree in Electronics and Communication Engineering from the Army Institute of Technology, Pune University, Pune, India, in 2002. He is currently working as a Scientist with DRDO-MTRDC, Bengaluru, India. He is pursuing the PhD at the Indian Institute of Science, Bangalore. His research interests include computational Electromagnetics, CAD and development of traveling-wave tubes. He is a member of the VEDAS and the Indian Science Congress Association.
In the current study, he has supported the work by verifying the simulation results.

Dr Subrata Kumar Datta received his BE in Electronics and Telecommunication Engineering in 1989 from Bengal Engineering College, Shibpur, India, and MTech and PhD in Microwave Engineering in 1991 and 1999, respectively, from the IIT-BHU, Varanasi, India. He is currently a Scientist with DRDO-MTRDC, Bengaluru, India. His current research interests include vacuum electronic devices and electromagnetic propagation in conventional and un-conventional circuits. He is recipient of a number of national awards. He is a member of the National Academy of Sciences (India) and Senior Member of the IEEE, USA. He is Fellow of the IETE, the IEI and the VEDAS.
In the current study, he has been the originator of the task and assumed the guiding role.