Recent advances on both numerical and experimental multipactor predictions

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ABSTRACT

CNES, the French Space Agency, has been studying space high power radio frequency (RF) effects – Multipactor, Corona and Passive Intermodulation – for many decades, starting from J. Sombrin Multipactor theory and models [1] to ongoing activities covering TRL[1] from 1 to 7 with our collaborators from academia, agencies, and industries.
This paper intends to discuss recent advances related to Multipactor analysis, and present our way towards our main objective in this field: to improve modelling and experimental Multipactor predictions and the synergy between the two. We are studying electron emission physics to enhance our models and measurement methods on dielectric materials, their TEEY[2], charge dynamics, treatment of secondary and backscattered electrons and the impact on Multipactor predictions. We are developing SPIS[3] to create a robust Multipactor modelling tools, dealing with dielectric materials and electron sources, while considering couplings with current reference software such as CST Studio, Spark3D and ANSYS Multipaction. We are also studying multipactor mitigation techniques based on surface treatments for both conductor and dielectric materials, and RF components design innovations to deal with current trends such as miniaturisation and high performances leading to high power density hence Multipactor risks.
These studies align with the European roadmap on Multipactor theme [2] and complement ESA funded activities. We share the main goal as to give our community experimental and numerical tools to get better Multipactor predictions to, in fine, improve the reliability and performances of our high power RF systems.
As a national agency we also engage on community awareness, explaining to various space communities that high power effects should be a common concern, and robust analyses should be better integrated in development plans and not wait for an anomaly and/or a major satellite loss to happen.

[1] TRL: Technology Readiness Level
[2] TEEY: Total Electron Emission Yield
[3] SPIS: Spacecraft Plasma Interaction Software

1. INTRODUCTION

Multipactor effect or phenomenon is often associated with a risk, Multipactor breakdown; when the power of a radio-frequency (RF) signal propagating in a RF component in vacuum gets above a certain threshold an electron cloud can develop. Specific conditions on the electromagnetic (EM) wave, the electrons trajectories in vacuum and the electron-surface interaction are necessary [3]. Such electron density increase can lead to undesired effects from RF signal perturbation to electrical breakdown (the vacuum medium conducts instead of isolates). In space applications such as satellites payloads where RF components are key elements to communicate with other satellites or earth ground stations, we cannot allow such phenomena to happen, hence power margins are applied to RF performances. The multipactor effect is also studied in other scientific fields like particle accelerators [4], nuclear fusion reactors (Tokamaks) [5], power amplifiers (e.g. travelling-wave tube). To predict the multipactor threshold, the power (or electric field strength) at which the electron cloud could develop, one can perform experimental tests or use numerical tools [6]. The latest versions of the ECSS[4] [7,8] on Multipactor are key documents to understand such phenomenon, the methods to predict it, and the associated breakdown risk margins. Another key document is the European Space Technology Harmonisation Dossier on “Power RF measurements and modelling” [2] which explains the main issues the community is still facing and the planned activities (R&D[5] line) to tackle them.

Multipactor effect is complex as it involves multiple physics: (i) RF wave (electromagnetism), single carrier, multicarrier and modulated signal operations (ii) particle and wave interaction, (iii) particle and material surface interaction, (iv) material properties especially electron emission from low energy incident flux, and (v) particle-particle interactions (electrons but also neutral and ions), while all of those can more or less influence one another. Having numerical tools that can rigorously modelled all these physics and the coupling between each of them is very challenging. It remains a long-time objective and will definitely need experimental campaigns to validate the many developments to come. We also need to progress on modulated signals and multicarrier operation scenarios, to improve our characterisation of dielectric materials and their modelling, to develop experimental methods to assess the physics of a laboratory-induced multipactor breakdown, and seek innovative RF components and systems that could withstand high power densities. Such a list cannot be exhaustive but summarise some of the main challenges the community encounters, and somehow tells much on why power margins are recommended by the ECSS [7,8].

This paper intends to introduce recent activities related to Multipactor analysis which are technically and financially supported by CNES, the French Space Agency; some of these activities will have a dedicated presentation during MULCOPIM conference.
Our current activities focus on electron emission physics to enhance our models and measurement methods on dielectric materials, their TEEY[6], charge dynamics, treatment of secondary and backscattered electrons and the impact on Multipactor predictions (more in section 4). We are developing SPIS to create a robust Multipactor modelling tools, dealing with dielectric materials and electron sources, while considering couplings with current reference software such as CST Studio, Spark3D and ANSYS Multipaction (see section 5). We are also studying multipactor mitigation techniques based on surface treatments for both conductor and dielectric materials (section 6), and RF components design innovations (section 7) to deal with current trends such as miniaturisation and high performances leading to high power density hence Multipactor risks.

Before diving into the activities, we discuss the current trends for Multipactor breakdown analyses (section 2) and present French actors and capabilities (section 3).

It’s important to remember that one of the key parameters of Multipactor phenomenon is the electron emission properties of the surfaces, especially secondary electron emission (SEE). If one can reduce the emissivity of the surface to make the total electron emission yield (TEEY) below unity for any incident electron energy than Multipactor electron avalanche cannot develop. Keeping this in mind, it’s easier to comprehend why a fair amount of R&D activities concentrate on surface characterisations and treatments.

[4] ECSS: European Cooperation for Space Standardization
[5] R&D: Research & Development
[6] TEEY: Total Electron Emission Yield

2. CURRENT TRENDS (FROM A CNES POINT OF VIEW)

Classic market demands are for payload equipment with higher RF power and faster time to market, leaving little time for rigorous RF breakdown assessments. Now if we add a need for higher frequencies, broadband and complex RF signals (e.g. modulated) operations then we get an unavoidable increase of high power densities on-board leading to an increase of the risk to have RF breakdown, hence failures, in telecommunication systems. To cope with these demands, European institutions, companies and universities are increasing their workforce on RF breakdown phenomena, especially on Multipactor analyses.
Another difficulty is to support *New Space* actors with no or low knowledge on such phenomena and associated risks. It requires more supports from technical experts, when risks are identified which is not always the case. Community and space project management awareness is then of paramount importance; European institutions play an essential role in that aspect to make sure RF breakdown analyses are well integrated in development plans to mitigate planning and cost risks. National and international workshops (e.g. MULCOPIM) are also key efforts to progress.

To meet market demands, RF systems become more and more complex with new architecture and materials; this increases uncertainties from the usual power handling analyses and emphasises on the need of test campaigns and qualification measurements. A challenging difficulty appears when dielectric materials are used (more and more common): electron emission properties for conductor materials are well established both experimentally and numerically but this is not the case for dielectrics. Electron emission properties can vary during the multipactor electron discharge since charge carriers (e.g. electrons and holes) inside the material cannot move freely in dielectrics. It is then difficult to reliably measure electron emission properties from dielectrics. We work to improve our measurements methods as well as numerical models (analytical and probabilistic) for dielectrics to be able to capture their electron emission properties dynamic in Multipactor simulation.

We also identify an emerging need for Multipactor analysis in RF components with triple point configurations, e.g. dielectric-metal-vacuum in microstrip lines or RF connectors. The complexity of the interactions between the EM wave, electrons and materials surfaces makes any numerical prediction uncertain.

While adding complexity in RF systems is inevitable, there are also extensive researches on mitigation techniques to reduce the risk of multipactor discharge, especially methods to reduce surface electron emissivity which directly relate to an increase of usable RF power.

3. FRENCH CAPABILITIES AND ACTORS

CNES has been studying space high power radio frequency effects – Multipactor, Corona and Passive Intermodulation – for many decades, starting from J. Sombrin Multipactor theory and models [1] to ongoing activities covering TRL from 1 to 7 with our collaborators from academia, agencies, and industries. Along the way many collaborations have naturally been created with institutions, research centres and industries not only in France but internationally as well. Table 1 gives a hint of capabilities from French actors working with CNES on Space applications. Note that Table 1 does not include entities working in other related field like particle accelerators or nuclear fusion reactors (Tokamaks).

Table 1. French actors and capabilities (experimental and modelling) in Multipactor and electron emission analyses.

French Entities		Multipactor		Electron Emission	
		Experimental	Modelling	Experimental	Modelling
Research Centres	**ONERA**	R&D test bed with CNES and multiple activities in collaboration with CNES, French industry and ESA-VSC.	Development of SPIS, and use of commercial Software	State of the art facilities for both metals and dielectrics.	State of the art SEY models considering backscattered and secondary electrons.

	TéSA	Multiple activities in collaboration with CNES and French industry.	Theoretical and numerical models.	Activities in collaboration with CNES and ONERA.	Most relevant SEY models considering the first cross-over energy (E_{C1}).
	Lab-STICC	Multiple activities in collaboration with French industry and ESA-VSC.	Extensive use of commercial Software for RF filters	Activities in collaboration with CNES and ONERA.	Activities in collaboration with CNES and ONERA.
	CNRS	Experimental setup for frequencies between 10 MHz and 1GHz.	Extensive use of commercial software for cavities used in particle accelerators.	Activities in collaboration with CNES and ONERA.	
Industries	**Artenum**	Activities in collaboration with CNES	SPIS, ECSS Multipactor Tool, Iris-SEY developments.	Activities in collaboration with CNES and ONERA.	Activities in collaboration with CNES and ONERA.
	Space Industry #1	CW, Pulse, multicarrier, and modulated signals over multiple frequency bands. Temperature control and various vacuum chambers.	Extensive use of commercial Software.	Activities in collaboration with CNES and ONERA.	Activities in collaboration with CNES and ONERA.
	Space Industry #2	CW and Pulse modes with temperature control over multiple frequency bands. Specific expertise on tests with ferrites.	Extensive use of commercial Software.	Activities in collaboration with CNES and ONERA.	Activities in collaboration with CNES and ONERA.
	Space industry #3	CW and Pulse modes with temperature control over multiple frequency bands.	Extensive use of commercial Software.		

The colour code for Table 1 is the following: green means internal expertise/tools, orange stands for shared expertise/tools, while red indicates the absence of ongoing collaboration or activities.

In the following sections we discuss some of our current activities focus on electron emission physics (section 4), development of SPIS (section 5), surface treatments for both conductor and dielectric materials (section 6), and RF components design innovations (section 7). When specified, references with the format [i], [ii], …, [iv] mean that there is another contribution during MULCOPIM 2025.

4. DIELECTRIC MATERIAL PHYSICS, MEASUREMENTS AND MODELS

One of the main limitations to current multipactor predictions, both experimental and numerical, is to get a clear knowledge of electron emission properties (charge, dose, electron emission) of dielectric materials[7]. For such materials, these properties vary when the surface is under radiation (particles, fields) making the measurements of the total electron emission yield (TEEY) challenging. For conductors, some of the charge carriers are free to move making the surface TEEY more stable. On top of the material aspects, the electrical conductivity genuine difference between conductors and dielectrics would also alters the synchronism between electron trajectories in vacuum and the RF electric field which is one of the necessary conditions for Multipactor effect to occur.

[7] Note that here lies a reason on why ECSS power margins [7,8] are much higher when RF components include dielectric materials.

In contribution [i] some of these challenges and how we approach them are discussed, with recent results on measurements of TEEY on dielectrics, and modelling works on both the materials physic and its effect on multipactor threshold numerical predictions.
Contribution [ii] focuses on the experimental methods to measure TEEY on dielectric materials. We propose key modifications to the conventional Kelvin probe (KP) method to improve the reliability of the measurements and its implementation. Some of the progress and results have been published [9].

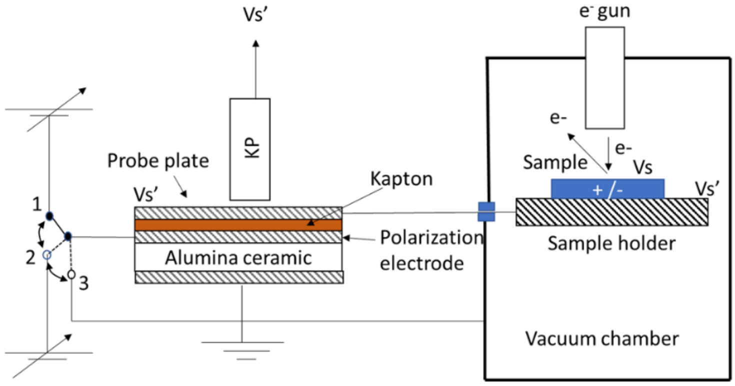

Fig. 1. Newly developed KP method experimental setup [9]

These activities are in synergy with numerical modelling efforts to develop accurate tools to simulate electron emission (EE) from dielectric materials. Low-energy (< 1 keV) electron transport presents specific challenges compare to higher energy electron transport: while high-energy interaction is often described using mean ionisation potentials or materials' electrons binding energies, for low-energy interaction the situation is quite different with mechanisms involving collective excitations (plasmons). To obtain numerical models for dielectric materials, one need to know the complex dielectric function of the material. Much more details on the physics and our recent progress are included in the contribution [iii], with discussions on the Microelec module (Monte-Carlo approach) within the GEANT4 framework. Low-energy ([eV, keV] energy range) transport simulations for a set of 17 materials (Be, C, Al, Si, Ti, Fe, Ni, Cu, Ge, Ag, W, Au, BN, Al_2O_3, TiN, SiO_2, Kapton) are consolidated.
Another activity focuses on modelling 2D graphene-based material since it is known to have low electron emissivity [10] while having suitable thermal, mechanical and optical characteristics. In the contribution [iv] our current effort to investigate the dielectric response of supported Multi-Layer Graphene (MLG), within the framework of the Layered Electron Gas (LEG) model, is presented and recent results confronting the model with experimental date are discussed.

5. SPIS, A PROMISING NUMERICAL TOOL.

Giving an exhaustive list of all the tools analysing multipactor phenomenon is a difficult task since a fair amount of the tools are private and/or dedicated to specific applications. We then find analytical, semi-analytical, or PIC (particle-in-cell) methods. The space community has users with commercial software such as Spark3D, CST Studio Particle and ANSYS Multipaction. These three software have demonstrated their capacity in simulating the EM field and calculating the electron trajectories in vacuum. Being commercial software make the codes availability difficult, and detailed physics of the electron-surface interaction as well as other models remain uncertain. In this context, the use and the development of an open source software dealing with the dynamics of the multipactor phenomenon appear to be crucial; it was decided to develop a multipactor model compatible with SPIS. This software is developed by ONERA (numerical core) and Artenum (HMI), and has been funded by ESA and CNES for more than two decades. Our choice has been motivated by the robustness of SPIS: one can model plasma-material interactions over a large range of scenarios, its numeric and physical models have been developed and validated since 2001 and is recognised worldwide by a dynamic scientific community (named Spacecraft Plasma Interaction Network in Europe).
A first step was to benchmark SPIS with CST Studio Suite which has been the subject of many activities and is known to be extensively used by the space community, along with Spark3D [11]. SPIS lacks of a Maxwell solver to calculate the electromagnetic field of RF waves so for now we can only study simple cases such as very narrow gap waveguide where the EM field can be calculated from analytical formulas. In the contribution [v] we discuss how to carefully setup CST

Studio and SPIS simulations, both numerical and physical parameters, to guarantee that both software results represent consistent multipactor analyses. We start with the simplest case, a uniform RF electric field in a narrow gap waveguide, and add RF complexity.

In parallel, we are also working on the coupling between CST Studio and SPIS, i.e. how to export 3D EM field calculated by CST Studio Microwave module and then to consistently import it in SPIS for Multipactor analyses. Once the workflow is consolidated, we aim to pursue past and current activities on studying the effect of dielectric material physics (surface potential, charge, dose, conductivity, field enhancement) on the multipactor's electron cloud dynamic, how the space environment could affect our analyses, and how multipactor and corona breakdowns are connected.

6. SURFACE TREATMENTS FOR BOTH CONDUCTORS AND DIELECTRICS

As mentioned many times, one way to reduce multipactor risks is to develop processes to get stable surface with low electron emissivity (while keeping other properties complaint with space applications). CNES role is to support French ecosystem (institution, industries and research centres) to develop or transfer technologies from low TRL to solutions for our industries to gain competitiveness. For innovative surface treatments we often test processes and materials from other scientific fields to see whether we can apply or adjust them to be compatible with space high-performance RF systems. We also need to comply with REACH[8] enforcements.

Usually to reduce electron emissivity, one can modify the chemical composition of the surface, its texture or both at the time. A challenge also lies in having a stable surface, i.e. a high-performance surface under tests in the lab must perform as such in operation on board.
Extensive researches look at nanostructures on the surface to get surface roughness conditions favourable for low electron emissivity (secondary electrons have higher probabilities to interact with the surface before being energetic enough to create other secondary electrons, $E>E_{C1}$).

Current activities focus on carbon thin layers, multi-layers deposition with different techniques such as FCVA[9], HiPIMS[10], CVD[11], and ALD[12].
Another promising method that we are exploring is to use electrodeposition for silver coating [11]; the surface presents micrometric and submicron roughness that reduces the silver TEEY (Fig. 2). Now we want to test these results on an actual high power RF components.

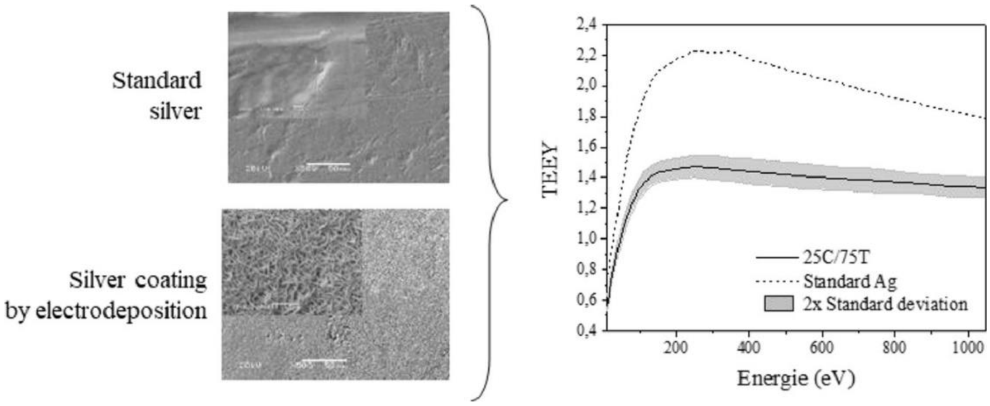

Fig. 2. TEEY reduction with silver coating by electrodeposition (figure adapted from [11]).

[8] Registration, Evaluation, Authorization, and Restriction of Chemicals
[9] FCVA: Filtered Cathodic Vacuum Arc
[10] HiPIMS: High-Power Impulse Magnetron Sputtering
[11] CVD: Chemical Vapor Deposition
[12] ALD: Atomic Layer Deposition

7. RF COMPONENTS DESIGN INNOVATIONS

While we have discussed few ways to reduce multipactor risks, we haven't yet mentioned how RF component design can be a very efficient path to increase multipactor power threshold. Power handling consideration should be included during the design phase to avoid planning and cost risks; by identifying early on where the critical areas prone to Multipactor are, one can modify the design to relax power handling constraints while maintaining RF electrical properties. We often look for small gap areas where electric fields are enhanced. Not all RF structures can allow such geometrical flexibility but some do. Excellent examples are RF filters using coaxial stepped impedance resonator (SIR) topologies (Fig. 3) [13]. These structures are convenient to reduce the size of coaxial lines or resonators, and have geometrical degrees of freedom giving some flexibility to comply with difficult specifications on electrical performance, power handling, size/volume, quality factors (Q), low insertion loss, flat passband, and large stopband. By controlling the cylinders' dimensions, connections and spacing we can design filters with high power handling for a relatively small volume (Fig. 3) while having some rare flexibility to control the frequencies of the fundamental, harmonics, and transmission zeros.

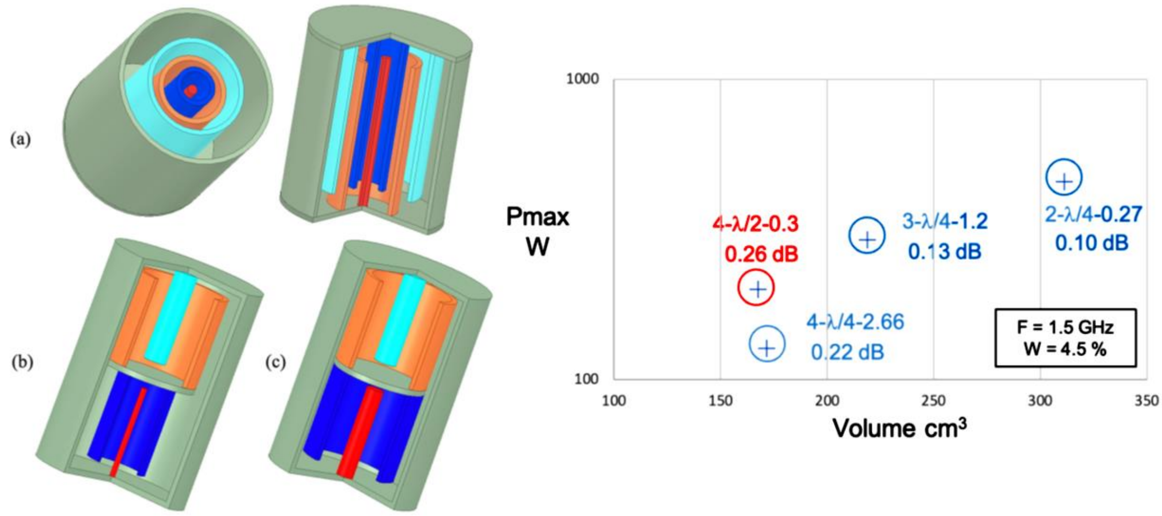

Fig. 3. Adapted from [13]; (left) Three-dimensional cut views of four-section coaxial SIRs. (a) Quarter-wavelength. (b) Asymmetrical open-end half-wavelength. (c) Symmetrical open-end half-wavelength. (right) Comparison of the multipactor threshold according to the volume for two four-, one three-, and one two-section coaxial SIR aluminum filters with identical bandwidths.

In contribution [vi] further work is discussed on how to implement DC electric field and/or dielectric materials in such RF filter topologies to influence the multipactor electron avalanche dynamic. Our first step was to use ANSYS HFSS, CST Studio and Spark3D software to compute both RF and DC fields with several SIR configurations. Once consolidated we will manufacture the optimal RF filter as proof of concept for power handling improvement.

8. CONCLUSION AND PROSPECTS

Rigorously predict multipactor threshold at which space RF system are at risk of electrical breakdown remains a challenge, especially with the trend to use more and more complex materials (e.g. composite, dielectrics, …) and structures while reducing the time to market for innovative RF equipment. Power margins recommended by ECSS standard are of paramount importance in this context. To bring more confidence in our predictions and then reduce the risk from RF breakdown we are working on many fronts.

This paper introduces recent activities related to multipactor analysis which are technically and financially supported by CNES, the French Space Agency; main subjects discussed are electron emission physics, surface treatments to reduce surface electron emissivity, and RF components design innovations. We also emphasis on the advantages of the use of SPIS for multipactor modelling, and its coupling with the numerical tools that are commonly used by the multipactor community.

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