9th International Workshop on Microwave Discharges: Fundamentals and Applications

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Multipactor RF Breakdown Analysis in a Parallel-Plate Waveguide Partially Filled with a Magnetized Ferrite Slab

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[3] Instituto Universitario de Matemáticas y Aplicaciones, Universidad Jaume I, Castellón

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[7] European Space Agency/European Space Research and Technology Centre, Noordwijk

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- Multipactor simulation algorithm
- RF Electromagnetic field computation
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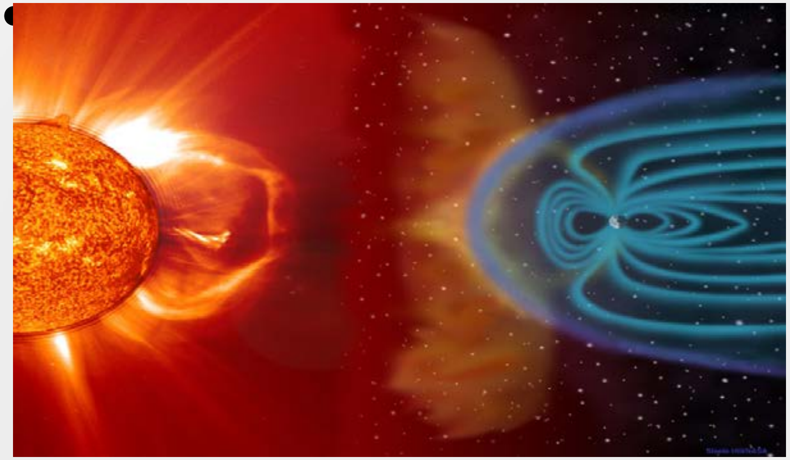
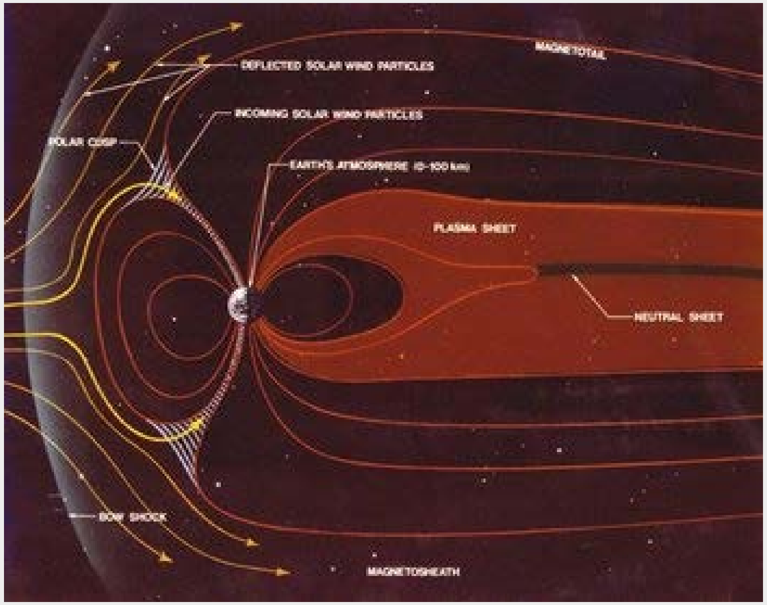
Introduction

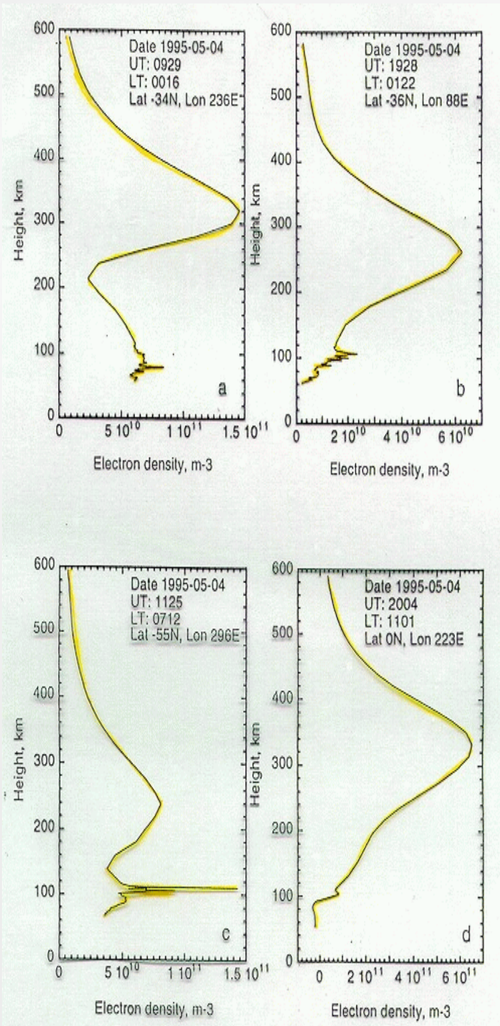
- Space weather is a very hostile environment

- Solar activity causes a continuous flux of high energy elemental particles towards the spaceships





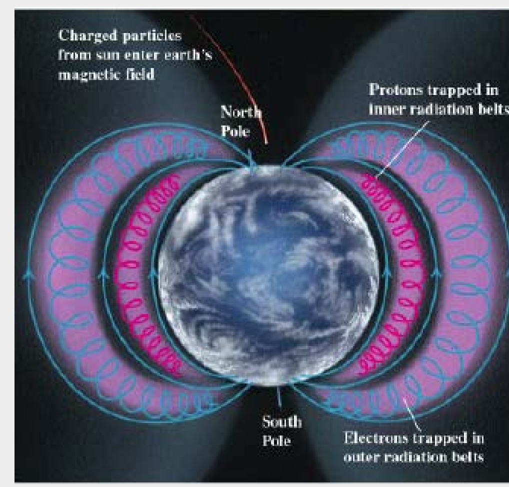
Introduction



- Electron density versus heigth (related to Earth surface) for different Earth points demonstrates a very high population of electrons around 300 km
- In a satellite: Cosmic radiation, Sun (fotoelectric effect), and Van Allen rings (1000-5000 km)

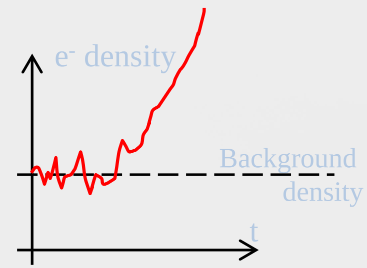
Initial electron density requested for a multipactor discharge in a Ku band component:

$\rho \sim 5\ 10^{10}$ electrons/m^3

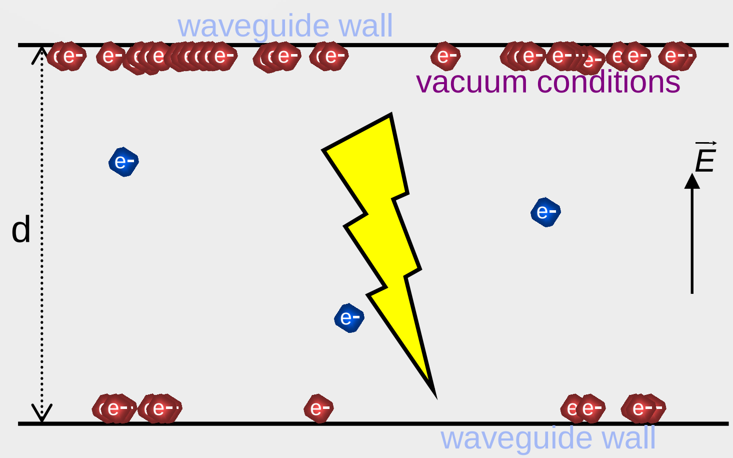


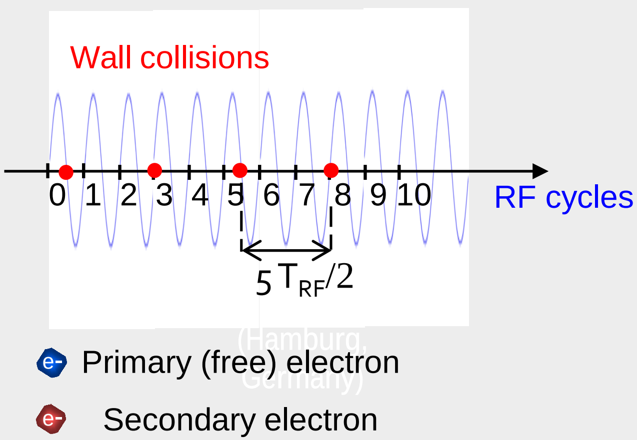
Introduction

Multipactor effect: electrons avalanche generated by the synchonization between an intense RF electric field and the secondary electron emission phenomenon (SEY) under ultra high-vacuum conditions.



Multipactor simulation in a parallel-plate waveguide region driven by a time-harmonic electric field





Introduction

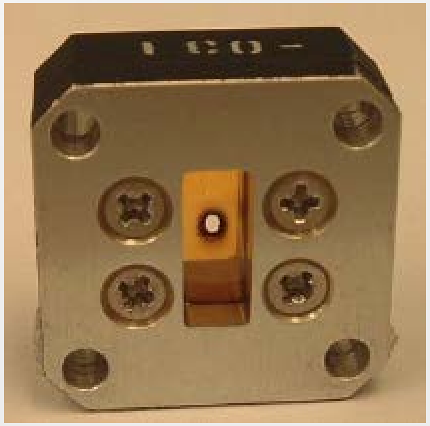
- Typically, multipactor phenomenon occurs in microwave components operating under high-power conditions inmmersed in a ultra-high vacuum envoriment:
  - RF satellite components
  - Particle accelerators structures
- Multipactor effect depends basically of:

- Geometry of the analyzed component: electromagnetic fields
- Materials used in the construction of the device: metals, dielectrics, ferrites, etc.
- Excitation signal: single-carrier, multicarrier, digital modulation, etc

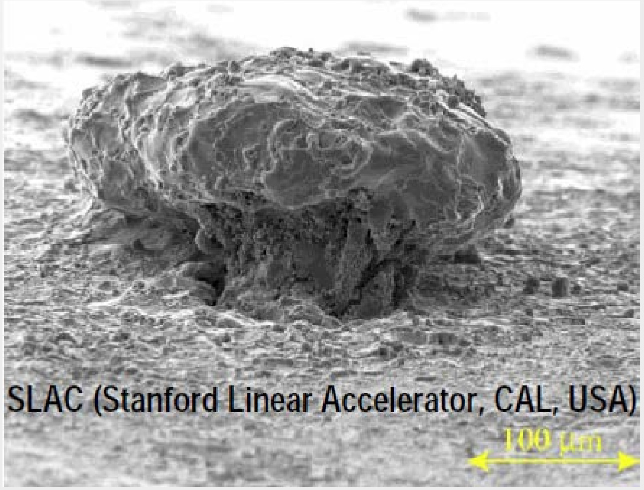
- Multipactor is unwanted: as a consequence, the prediction of the RF input power threshold of a specific component is a very important task.

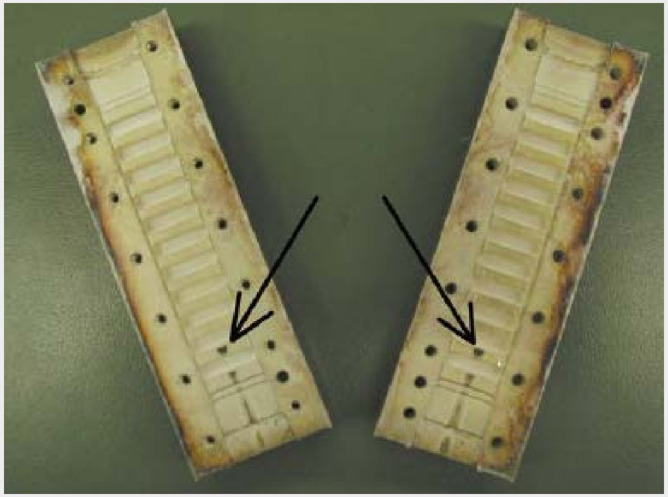
Introduction

- In these systems produces: noise, increase of the reflection coefficient, local surface heating, detuning electrical circuit, surface damage and possible breakdown of the component



Kapton window

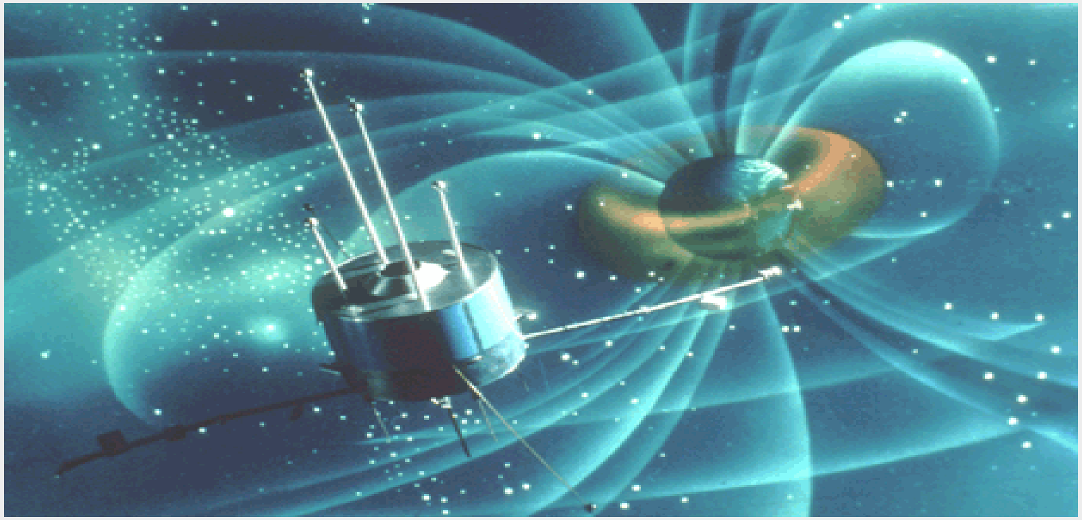




Low-pass filter

Introduction

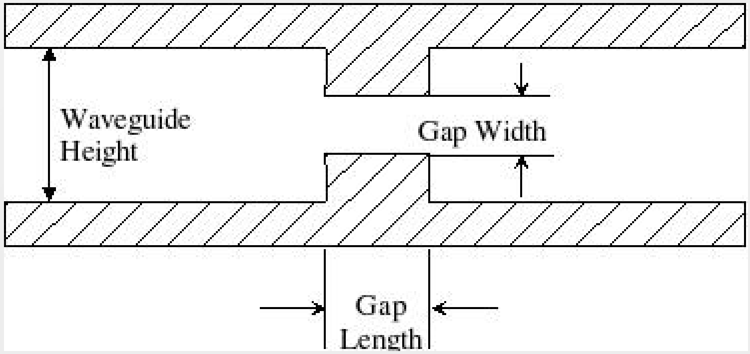
- In this undesired scenario the space agencies have to control and predict the possible existence of a multipactor discharge occurring within on-board microwave sub-systems: replacement of equipments is NOT POSSIBLE in a satellite …



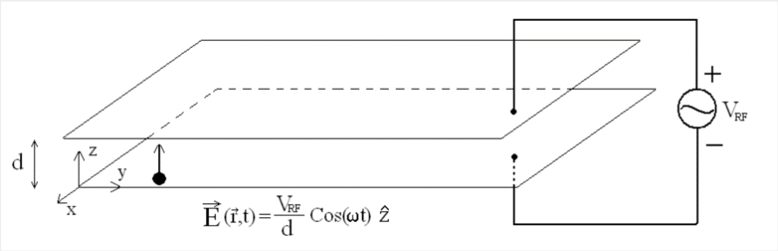
Introduction

- A simple theoretical model for multipactor analysis in a parallel-plate waveguide (PPW) was developed in the fifties and eigthies:

- Electrons motion is 1-D
- It is valid for rectangular waveguide, which is approached as a PPW
- Excitation is a single-carrier time-harmonic signal
- Equations are analytical



E-plane iris in rectangular waveguide



PPW scenario is similar to a capacitor driven by a time-harmonic signal

Introduction

This model has been formulated in two ways:

- Hatch&Williams model or k-model: velocities of the secondary electrons are proportional to the impact kinetic energy
- Sombrin model: velocity of the secondary electrons is constant

which generates slightly different susceptibility diagrams:

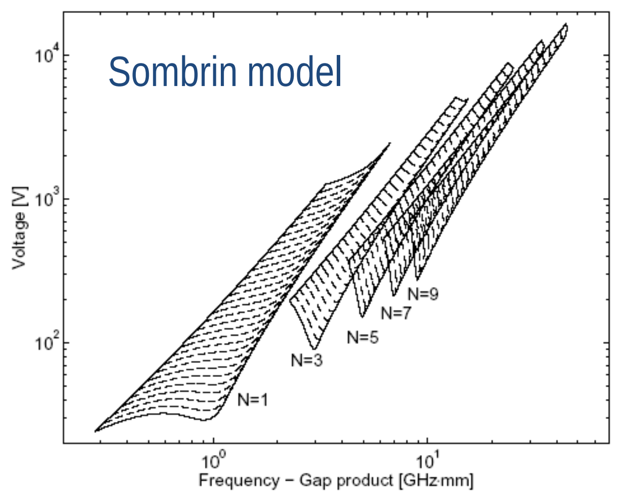


Figure 2.3: Multipactor susceptibility chart based on the constant initial velocity approach. Parameters used are: $W_0 = 3.68$ eV, $W_1 = 23$ eV, $W_2 = 1000$ eV, and $N_{max} = 9$.

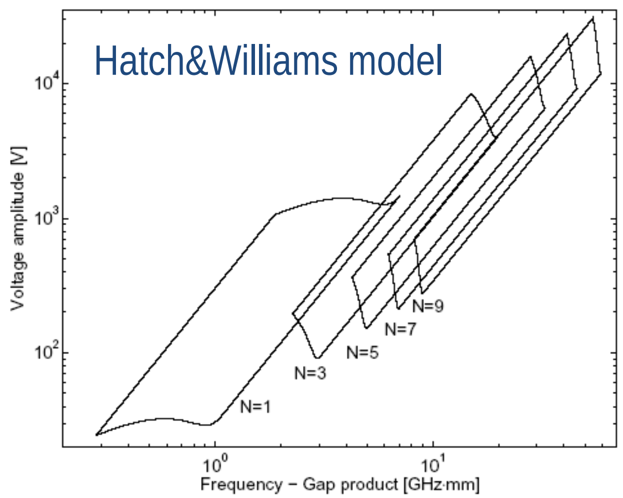


Figure 2.4: Multipactor susceptibility chart produced with the constant k assumption. Parameters used are: $k = 2.5$ (corresponding to an initial $W_0 = 3.68$ eV), $W_1 = 23$ eV, $W_2 = 1000$ eV, and $N_{max} = 9$.

Introduction

The experimental data obtained by Wood&Petit (ESA/ESTEC) in rectangular waveguide were matched with the Hatch&Williams model:

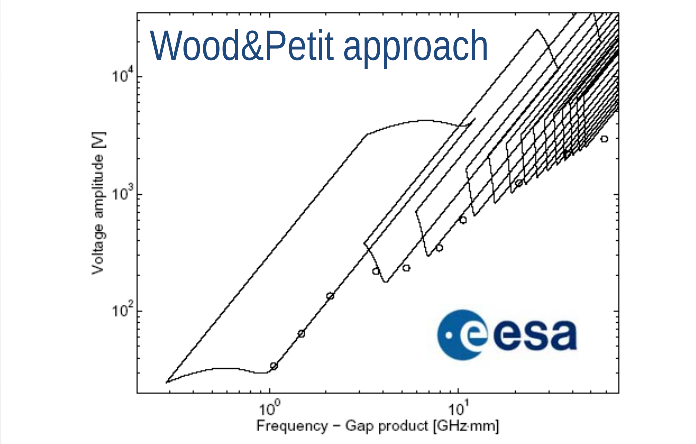


Figure 2.5: Hatch and Williams charts for aluminium together with measurement data by Woode and Petit [19].

- It is the theoretical base of the ESA ECSS Multipactor Tool
- This model analyzes the most pesimistic case for a multipactor discharge: in many cases it provides a <u>very low RF voltage threshold</u>

[1] A.J. Hatch, H.B. Williams, "Multipacting Modes of High-Frequency Gaseous Breakdown", The Physical Review, vol. 112, no. 3, pp. 681-685, Nov. 1958

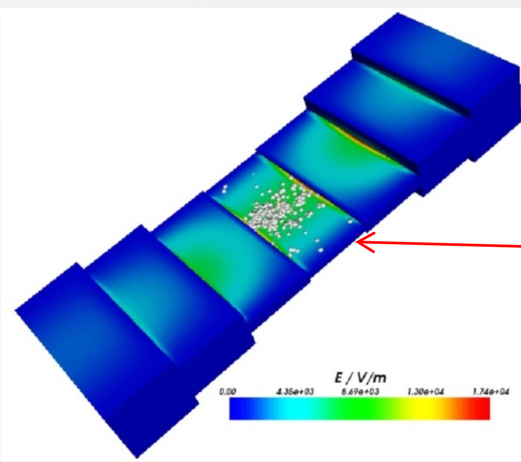
[2] J. R. M. Vaughan, "Multipactor", IEEE Trans. Electron Devices, vol. 35, no. 7, pp. 1172–1180, Jul. 1988

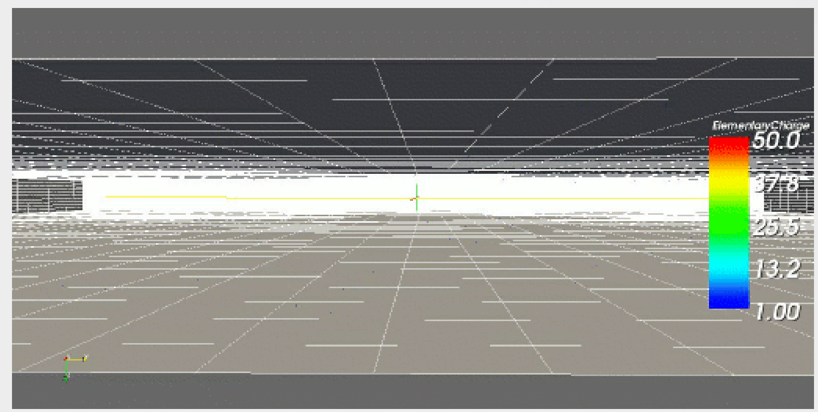
[3] J. Sombrin, "Effet multipactor", CNES, Toulouse, France, CNES Tech. Rep. No. 83/DRT/TIT/HY/119/T, 1983

[4] A. Wood and J. Petit, "Diagnostic Investigations into the Multipactor Effect, Susceptibility Zone Measurements and Parameters Affecting a Discharge", ESA/ESTEC Working Paper No. 1556, 1989

Introduction

- During the last 12 years multipactor analysis codes (FEST3D, SPARK3D, CST Microwave Studio) have been commerzialized:
  - These codes are able to tackle complex geometries but not with "complex" materials as ferrites





As a consequence, the analysis of multipactor effect involving complex media as dielectrics and ferrites has to be performed with a new software…

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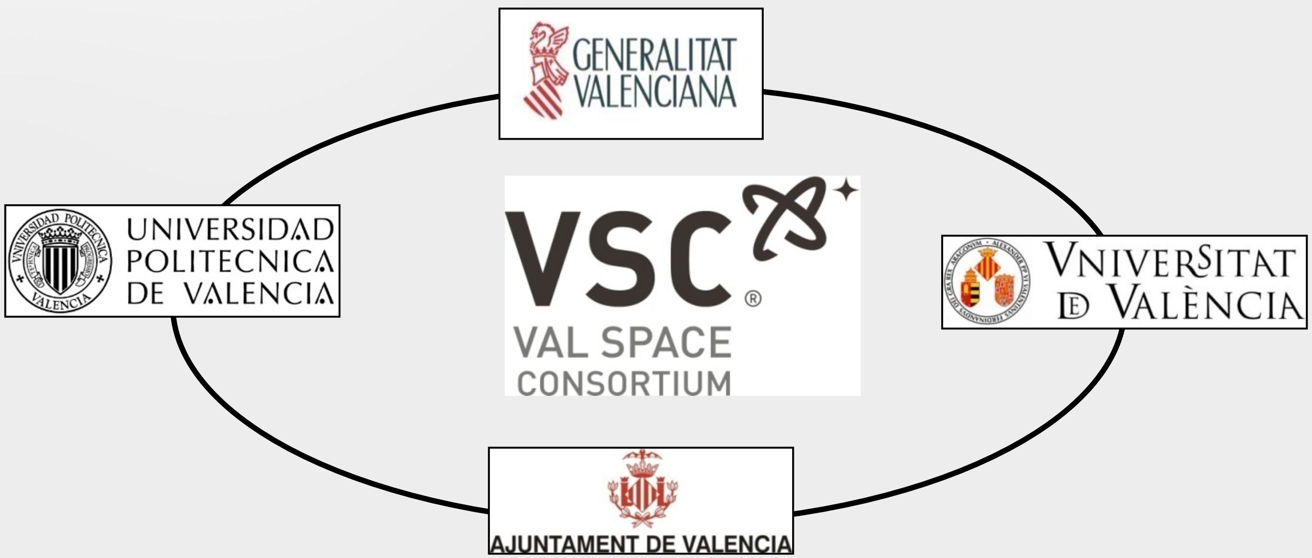
The VAL SPACE CONSORTIUM

- Val Space Consortium (VSC) is a public consortium
- Non-profit organization
- It is focused on providing testing services, consultancy, training and development of R&D activities in the Space field



The VAL SPACE CONSORTIUM

- The **contract signature** followed an announcement of opportunity issued during the summer of 2009 by ESA in search of a partner to provide competence and facilities to support to the operation, maintenance and development of the Laboratory.
- Among the proposals received, **VSC was selected**.
- On 25 March 2010, ESA and VSC signed a contract to jointly manage the European High Power RF Space Laboratory.
- ESA continues as the single **interface** for space-related testing activities.

The VAL SPACE CONSORTIUM

- **Objetives** of Val Space Consortium:
  - Activities about scientific research in space telecommunications sector
  - Technological development services in aerospace sector
  - Security and quality improvement for production of space systems and subsystems

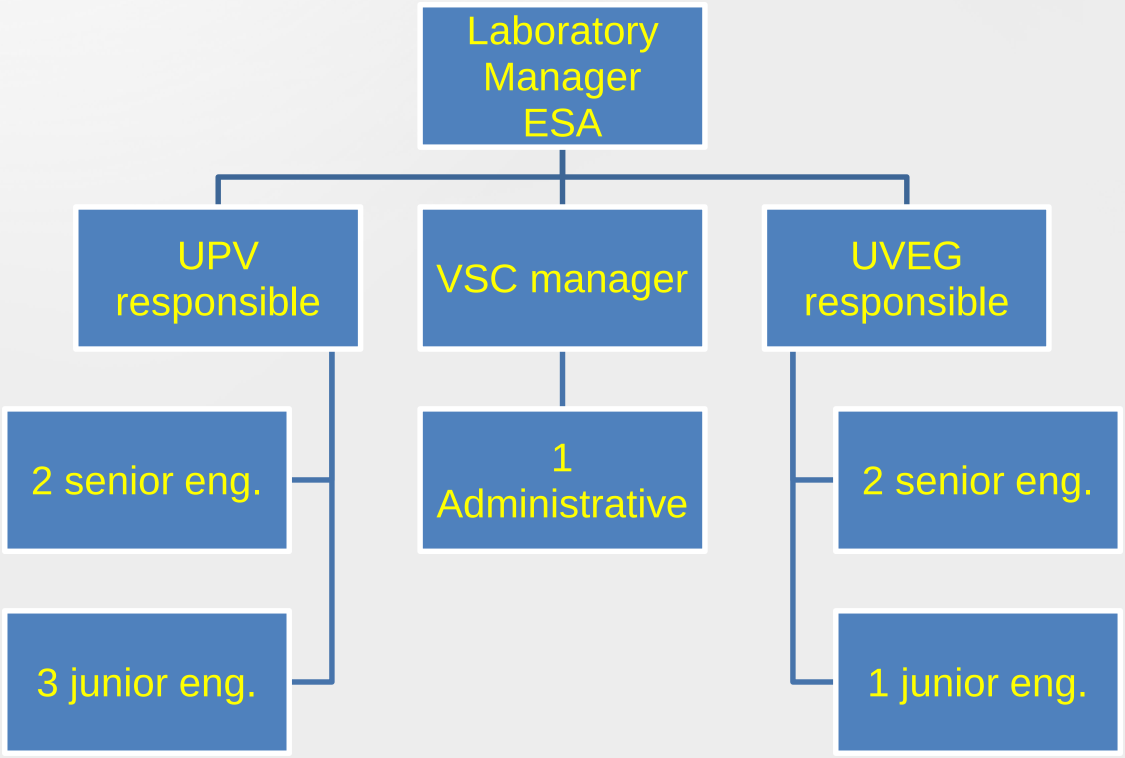
- All of these objectives will be achieved by means of:
  - Design and development of tests, analysis techniques, and diagnostic techniques for telecommunications space components operating under RF high-power conditions
  - Consultancy and certification of space subsystems of the telecommunications sector

The VAL SPACE CONSORTIUM

- Studies, reports, contracts and proyects about advising and regulation rules in the telecommunications space sector
- Programs of research and development in space technology sector
- Cooperation in masters, doctorate programs, seminars and congress
- Divulgation

The VAL SPACE CONSORTIUM

- Human Resources: Laboratory structure

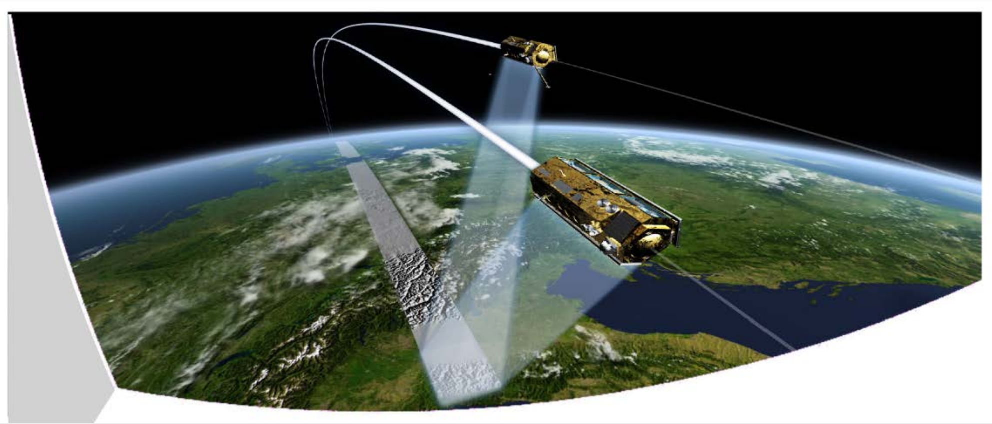


The VAL SPACE CONSORTIUM

- European High Power RF Space Laboratory: Opening of the Laboratory 28 June 2010

Technical Resources

- Test beds from 400 MHz to 50 GHz
- Around 40 RF power amplifiers (CW and pulsed)
- Waveguide (rectangular and circular), coaxial and microstrip
- Vector network analyzers, Spectrum analyzers, Oscilloscopes, etc …



The VAL SPACE CONSORTIUM

- Up to date the Laboratory can carry out these **tests**:
  - Multipactor effect: Single-carrier and Multicarrier
  - Corona effect
  - Power Handling
  - Passive Intermodulation (PIM): guided and radiated
- Next, the **facilities** of the Laboratory are presented.

The VAL SPACE CONSORTIUM

- Installed in the *Innovation Polytechnic City* (Technical University of Valencia):

The VAL SPACE CONSORTIUM

- Clean room 1 (150m^2) – Class 10,000

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- Clean room 2 ($50m^2$) – Class 10,000

The VAL SPACE CONSORTIUM

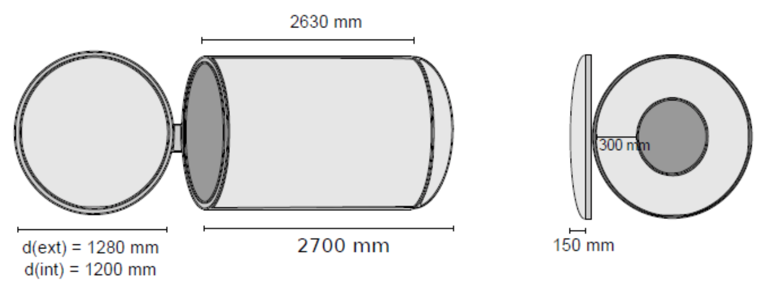
- Vacuum system 1

Chamber Dimensions	
Diameter	1200 mm
Depth	2700 mm

Base Plate Dimensions	
Length	120 mm
Width	345 mm

Pressure Range	
Maximum	1000 mbar
Minimum	10^{-6} mbar

Temperature Range
Not available



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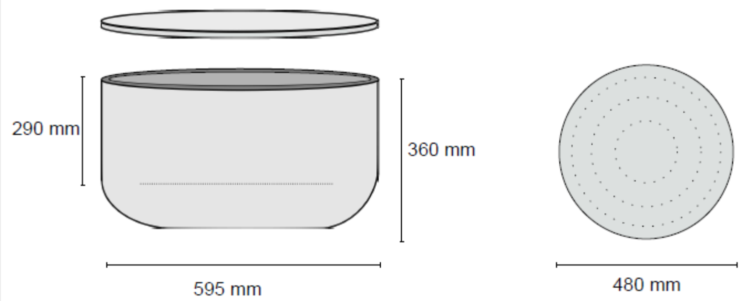
- Vacuum system 2

Chamber Dimensions		Base Plate Dimensions	
Diameter	595 mm	Diameter	480 mm
Depth	360 mm		

Pressure Range		Temperature Range	
Maximum	1000 mbar	Maximum	+140°
Minimum	10^{-7} mbar	Minimum	−40°



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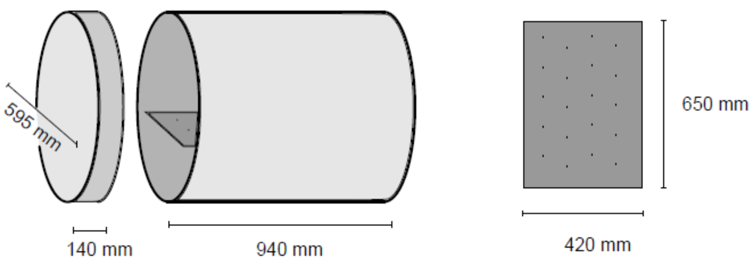
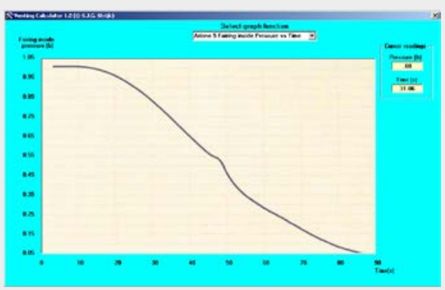
- Vacuum system 3

Chamber Dimensions		Base Plate Dimensions	
Diameter	595 mm	Length	650 mm
Depth	940 mm	Width	420 mm

Pressure Range		Temperature Range	
Maximum	1000 mbar	Maximum	$+130°$
Minimum	10^{-8} mbar	Minimum	$-65°$

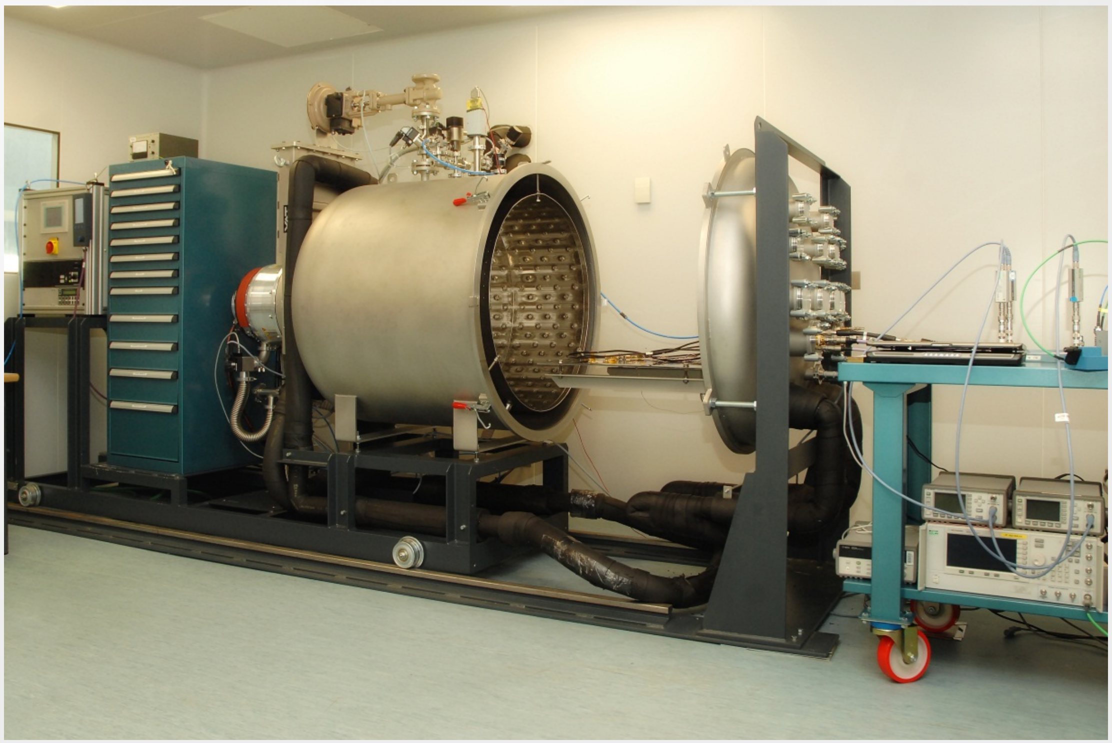


Pressure profile of Arian-5 rocket:



The VAL SPACE CONSORTIUM

- Vacuum system 4

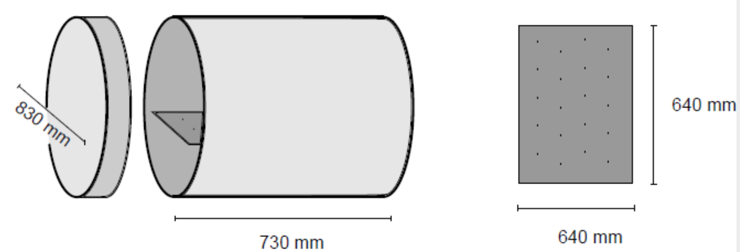


Chamber Dimensions	
Diameter	830 mm
Depth	730 mm

Base Plate Dimensions	
Length	640 mm
Width	640 mm

Pressure Range	
Maximum	1000 mbar
Minimum	10^{-7} mbar

Temperature Range	
Maximum	+120°
Minimum	−70°



The VAL SPACE CONSORTIUM

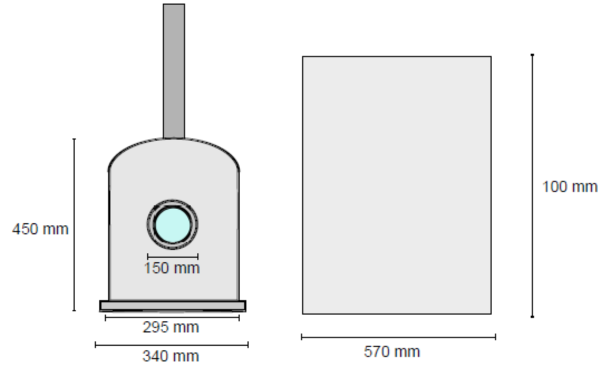
- Vacuum system 5

Chamber Dimensions	
Diameter	295 mm
Depth	450 mm

Base Plate Dimensions
Not available

Pressure Range	
Maximum	1000 mbar
Minimum	10^{-6} mbar

Temperature Range
Not available

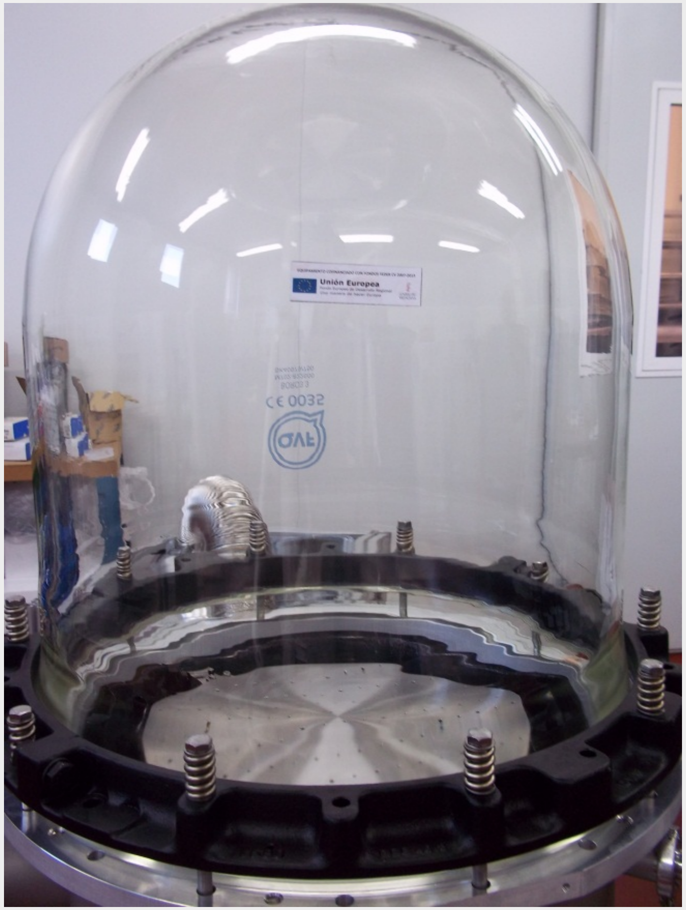


The VAL SPACE CONSORTIUM

- Anechoic chamber: PIM radiated

The VAL SPACE CONSORTIUM

- Dielectric radome for PIM measurements of antennas and radiating elements (10^{-6} mbar)



The VAL SPACE CONSORTIUM

- Multipactor-Multicarrier facility
  - 10 carriers of 400 watts each
  - Water cooled system
  - Fully automatic by software
  - Flexible and modular
  - State-of-the-art system
  - Unique in the World
  - Ku-band

The VAL SPACE CONSORTIUM

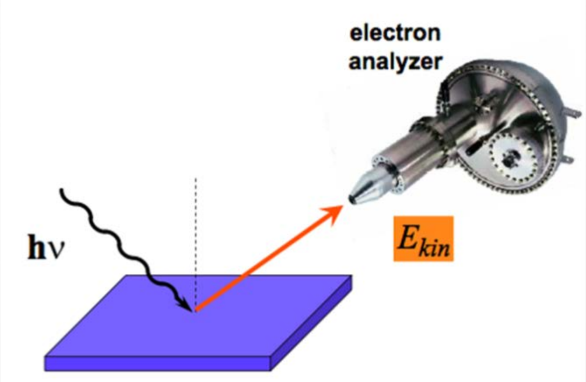
- European High Power Space Materials Laboratory:

  Inaugurated 9 July 2012

Installed in the *Technical School of Engineering* (University of Valencia):

The VAL SPACE CONSORTIUM

- X-Ray/Ultraviolet Photoelectron Spectroscopy (XPS/UPS)



Ultra high-vacuum

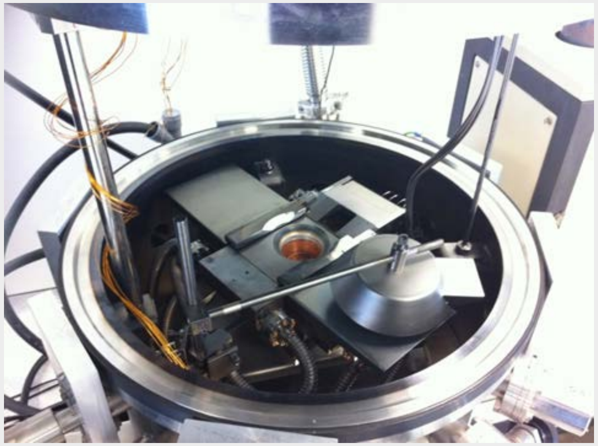
(10^{-9} mbar)

Measurement of SEEY for both metals and dielectric materials

The VAL SPACE CONSORTIUM

- Evaporation systems in high-vacuum (10^{-6} mbar)

Sputtering technique for low-SEEY multilayers growthing



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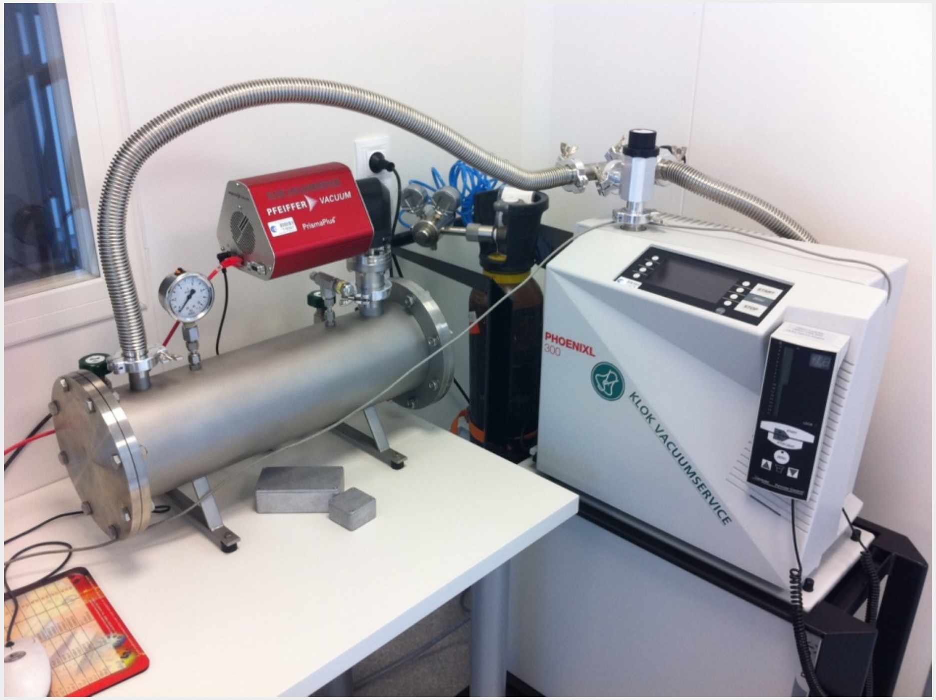
- Vacuum chamber for measurements of venting and outgassing phenomena (10^{-5} mbar) with a mass spectrometer



The VAL SPACE CONSORTIUM

- Other activities related with the Space Materials laboratory:
- Atomic force microscopy (AFM)
- Masses spectrometry
- Electronic microscopy
- Nuclear magnetic resonance
- X-Ray diffraction for mono-crystals and poli-crystals materials
- X-Ray fluorescence

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Objectives

Study of the multipactor effect in a parallel-plate waveguide with a magnetized ferrite slab:

- Computation of multipactor susceptiblity charts for some representative cases

- Analysis of the electron trajectories and the multipactor regimes

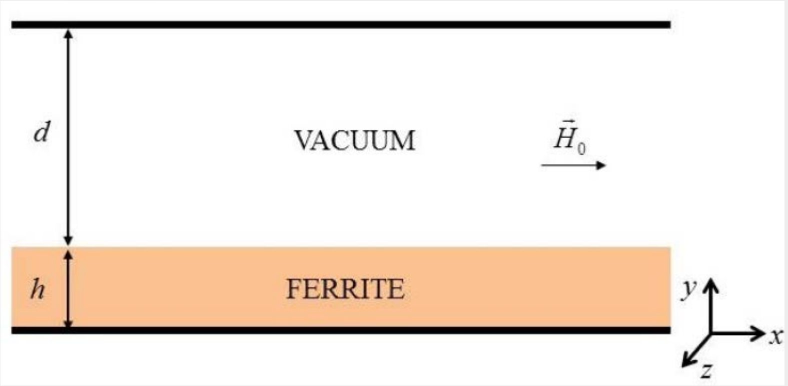
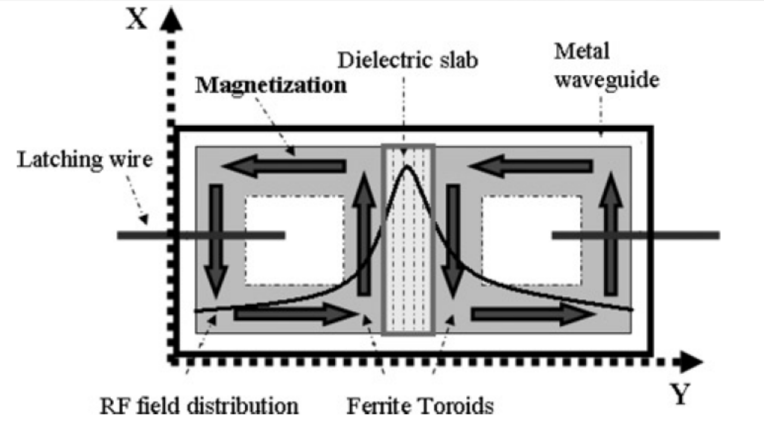


Figure: Transversally parallel to the surface magnetized ferrite slab

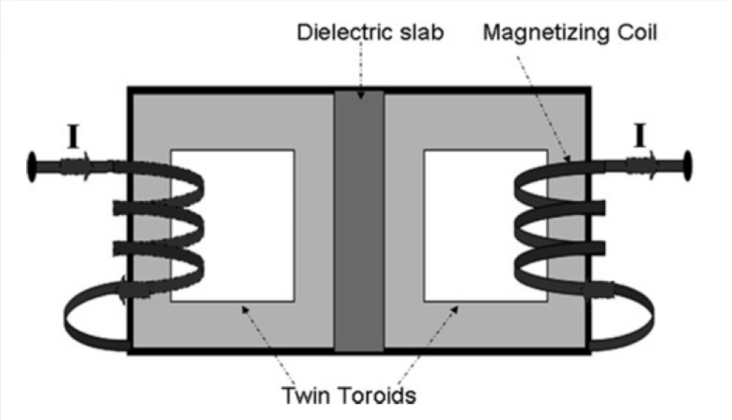
The parallel-plate waveguides is assumed to be infinite in the x-z plane

Objectives

The previous considered parallel-plate waveguide constitutes the first step to the understanding of more complex RF microwave devices containing ferrites such as some kind of high-power isolators and phase shifters



Frontal view of twin toroid phase shifter[1]



Twin toroid and its induction coil arrangement

[1]A. Abuelma'atti, J. Zafar, I. Khairuddin, A. Gibson, A. Haigh, and I. Morgan, "Variable toroidal ferrite phase shifter," IET Microw., Antennas Propag., vol. 3, no. 2, pp. 242–249, Mar. 2009

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Multipactor simulation algorithm

- The MONTE-CARLO algorithm is based on the tracking of a set of effective electrons governed by the TOTAL electromagnetic fields present within a specific microwave component region:
  - Initially, an effective electron is launched from a specific point with an initial velocity vector.
  - The trajectory of this effective electron is computed as a function of time.
  - When such effective electron impacts on a metallic/ferrite wall of the PPW, the SEY coefficient is computed, and the charge and the mass of the effective electron are *upgraded*.
  - Next, the considered *upgraded* electron is reemitted from the impact position with a random velocity vector.
  - The algorithm is stopped using a particular criterion.
  - Next effective electron is released…

Multipactor simulation algorithm

Effective electrons dynamics (3D):

Electrons motion is governed by the relativistic Lorentz force:

$$\overrightarrow{F}_L = q(\overrightarrow{E}_{\text{total}} + \overrightarrow{v} \times \overrightarrow{B}_{\text{total}}) = \frac{d\overrightarrow{p}}{dt}$$

$$\overrightarrow{p} = m_0 \gamma \overrightarrow{v} \qquad \gamma = 1/\sqrt{(1-(v/c)^2)}$$

where m_o is the electron mass at rest, q=-e is the electron charge, *v* is the magnitude of the electron velocity, γ is the relativistic factor, and

$$\vec{E}_{total} = \vec{E}_{RF} + \vec{E}_{sc} \qquad \vec{B}_{total} = \vec{B}_{RF} + \vec{B}_0$$

are the total electric and magnetic fields, including RF and DC contributions. $\vec{E}_{sc}$ is the electric field due to the space charge effect modelled by a single electron sheet, $\vec{B}_0$ is the external magnetic field applied to magnetize the ferrite.

The typical electron velocities values reached in space communication systems are lower than the speed of light in vacuum: the relativistic formulation can be approached considering that $\gamma \approx 1$,

Multipactor simulation algorithm

$$\vec{F}_L = q\,(\vec{E}_{total} + \vec{v} \times \vec{B}_{total}) = m_0\,\vec{a}$$

Finally the problem can be expressed as a coupled differential equations system of second order:

$$\vec{F}_L = q\,(\vec{E}_{total} + \vec{v} \times \vec{B}_{total}) = m_0 \frac{d\vec{v}}{dt} = m_0 \frac{d^2\vec{r}}{dt^2}$$

which has to be numerically solved.

Velocity-Verlet algorithm has been used for the numerical solution of the 3D differential equations system (≈ 300 time steps per RF period):

- Accurate
- Efficient
- Stable

L. Verlet, “Computer ‘experiments’ on classical fluids. I. Thermodynamical properties of Lennard–Jones molecules,” Phys. Rev., vol. 159, no. 1, pp. 98–103, Jul. 1967.

2nd order Taylor serie expansion for the position coordinate

$$x(t+\Delta t) = x(t) + x'(t)\Delta t + x''(x,t)\frac{\Delta t^2}{2} + \dots$$

$$x(t-\Delta t) = x(t) - x'(t)\Delta t + x''(x,t)\frac{\Delta t^2}{2} + \dots$$

→

$$x(t+h) = x(t) + h\,v(t) + h^2\frac{a(t)}{2}$$

$$v(t+h) = v(t) + \frac{h}{2}(a(t) + a(t+h))$$

Multipactor simulation algorithm

<u>Calculation of SEY at each impact</u>:

- At each integration step, we check if the effective electron strikes on a wall.
- If an impact occurs, the electron can be elastically reflected or can produce true secondary *individual* electrons.
- Then, the SEY coefficient has to be calculated: SEY = δ

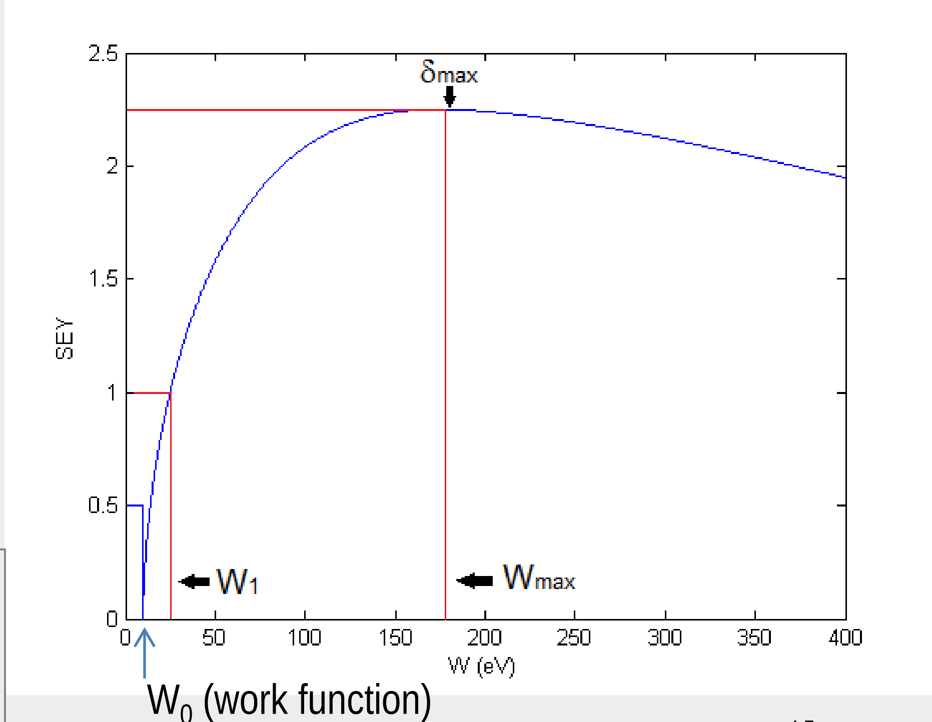
$$\delta \equiv \frac{\text{number of secundary electrons released}}{1\,\text{impacting electron}}$$

The SEY coefficient depends on:

- Kinetic energy of the primary electron.
- Incidence angle of primary electron (ξ).
- Surface roughness.

Model parameters for copper
(normal incidence: $\xi = 0$)

$W_1 = 25$ eV
$W_{max} = 175$ eV
$\delta_{max} = 2.25$



Multipactor simulation algorithm

SEY modified Vaughan's model

Equations of modified Vaughan's model

Kinetic energy of impacting electron

$$\delta(W,\xi) = \begin{cases} 1 & \text{si} \quad \gamma < 1 \\ \delta_{max}(\xi)(\gamma e^{(1-\gamma)})^{0,25} & \text{si} \quad 1 < \gamma \leqslant 3,6 \\ \delta_{max}(\xi)\frac{1,125}{\gamma^{0,35}} & \text{si} \quad 3,6 < \gamma \end{cases}$$

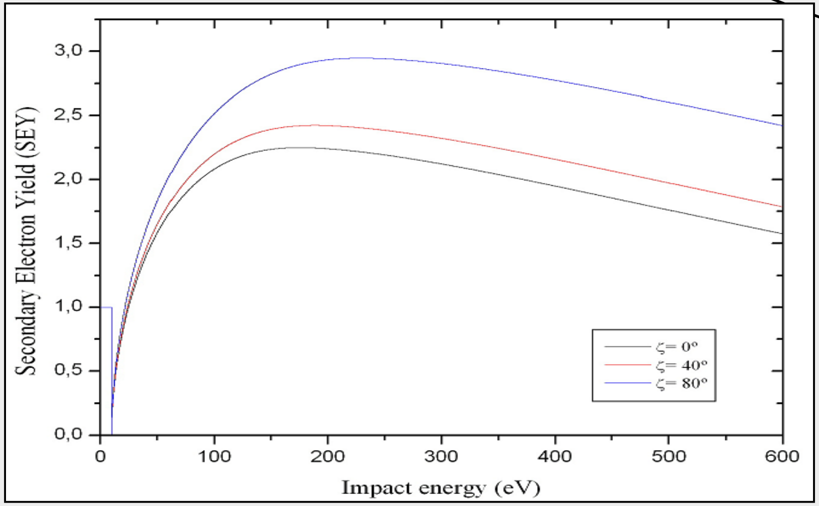
Incidence angle measured from the normal to the surface

Parameter obtained from continuity conditions of SEY

$$\gamma = \frac{W - W_0}{W_{max}(\xi) - W_0}$$

Maximum SEY value at normal incidence

Factors related to the surface roughness



$$\delta_{max}(\xi) = \delta_{max}(0) \cdot (1 + \frac{k_W \xi^2}{2\pi})$$

$$W_{max}(\xi) = W_{max}(0) \cdot (1 + \frac{k_\xi \xi^2}{2\pi})$$

Kinetic impact energy at $\delta_{max}(0)$

Multipactor simulation algorithm

<u>Departure conditions of the re-emitted electron</u>

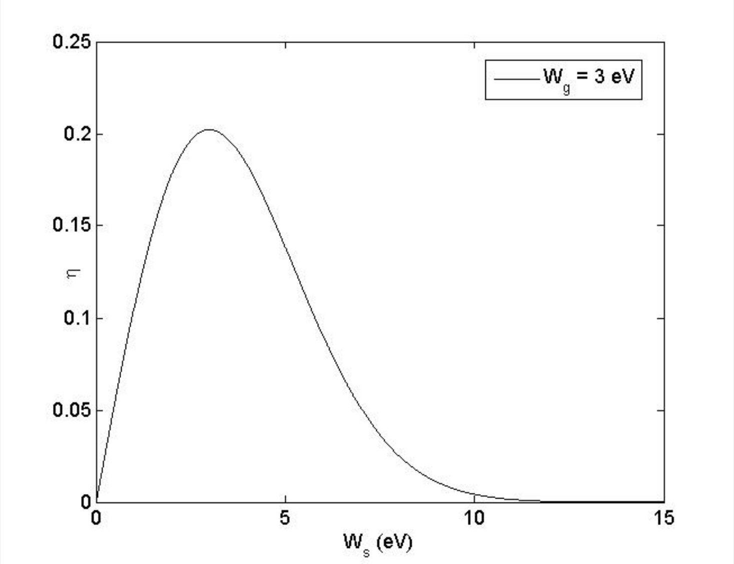
- If the impact kinetic energy $W < W_o$: effective electron is reflected as in a specular reflection (the magnitude of the velocity vector does not change).

- If the impact kinetic energy $W \geq W_o$: secondary individual electrons are released, but the effective electron assumes the total charge and mass of the real secondary electrons emitted:

The <u>magnitude of the velocity vector</u> of the effective electron is calculated by means of a Rayleigh probability distribution density:

$$\eta(W_s) = \frac{W_s}{W_g^2} \exp\left(-\frac{W_s^2}{2\,W_g^2}\right)$$

Normalization condition → $\int_0^{+\infty} \eta(W_s)\, dW_s = 1$



W_s = Departure energy of the secondary electron
$\eta(W_s)$ = Probability of release a secondary electron with a departure energy of W_s
W_g = Standard deviation value

Multipactor simulation algorithm

In order to implement this concept in the Monte-Carlo method, the algorithm generates a random real number r ∈ [0,1], and the departure energy is calculated:

$$W_s = W_g \sqrt{-2 \ln r}$$

Note the Energy Conservation Principle has to be satisfied.

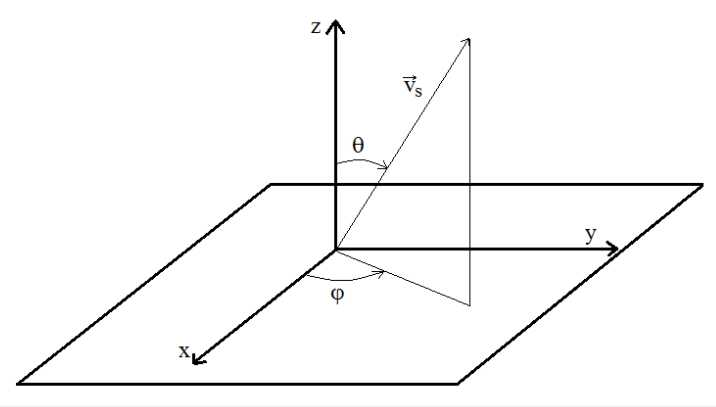
➢ The direction of the velocity vector of the effective electron is calculated in a local spherical coordinate system centred at the impact point:

- the azimuthal angle $\varphi \in [0,2\pi[$ is easily calculated by means of a uniform probability density:

$$\varphi = (2\pi) r$$

- the elevation angle θ has to be computed by means of the cosine law:

$$\theta = \arcsin \sqrt{r}$$

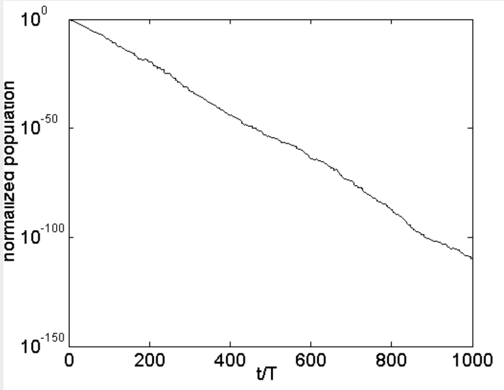


J. Greenwood, “The correct and incorrect generation of a cosine distribution of scattered particles for Monte-Carlo modelling of vacuum systems” , Vacuum, vol. 67, pp. 217–222, 2002

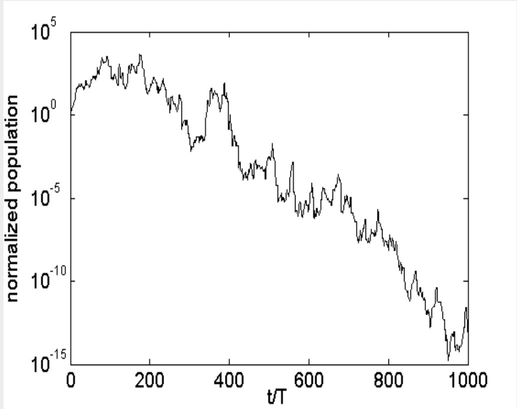
Multipactor simulation algorithm

Multipactor onset criterion

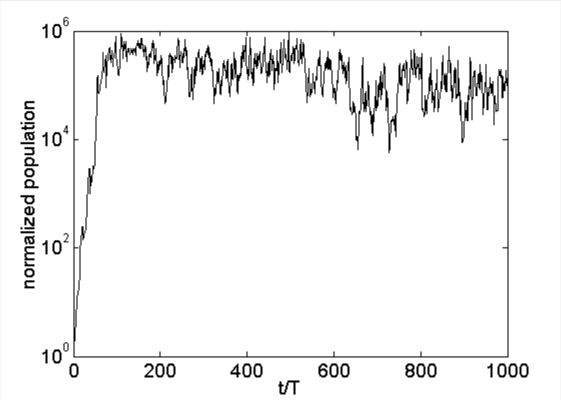
- A multipactor onset criterion must be stablished in order to determine if the multipactor discharge is present at a certain RF voltage level.
- Presence of saturation effect in the electron population is selected as the multipactor criterion.
- The minimum voltage level at which the multipactor discharge is present is known as the multipactor RF voltage threshold.



V_0 = 70 V



V_0 = 115 V



V_0 = 122 V

RF multipactor voltage threshold is **V_{th} = 122 V**

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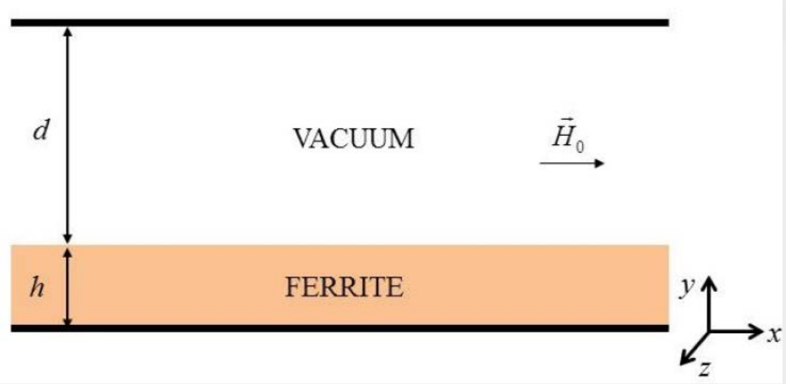
RF electromagnetic field computation

Ferrite magnetization parallel to the surface

- The external magnetic field employed to magnetize the ferrite slab is oriented in the *x*-direction.
- RF electromagnetic field is assumed to propagate along the possitive *z*-direction.
- An harmonic time dependence is implicitly assumed.
- Ferrites behave as ferrimagnetic materials when a DC magnetic field is applied. In this case, the magnetic anisotropy is described by the following permeability tensor:



Case 1: Transversally parallel to the surface magnetized ferrite slab

$$\overline{\mu} = \begin{pmatrix} \mu_0 & 0 & 0 \\ 0 & \mu & j\kappa \\ 0 & -j\kappa & \mu \end{pmatrix}$$

$$\mu = \mu_0 \left(1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2}\right)$$

$$\kappa = \mu_0 \frac{\omega \omega_m}{\omega_0^2 - \omega^2}$$

$$\gamma = \frac{e}{m}$$

$$\omega_0 = \mu_0 \gamma H_0$$

$$\omega_m = \mu_0 \gamma M_s$$

ω is the RF angular frequency

ω_0 is the Larmor frequency

ω_m is the saturation magnetization frequency

μ_0 is the vacuum magnetic permeability

γ is the gyromagnetic ratio of the electron

M_s is the saturation magnetization of the ferrite

RF electromagnetic field computation

- RF fields supported by the partially-loaded ferrite waveguide can be obtained analytically with the mode-matching technique solving frequency-domain Maxwell equations.
- Two families of electromagnetic field modes are found: TM^z (H_z = 0) and TE^z (E_z = 0).
- TE^z modes have no vertical electric field along the gap, so they are not suitable to hold a multipactor discharge. As a consequence, these modes will not be considered in this work.
- TM^z modes do have vertical electric field along the gap. The non-zero field components of such modes (in the vacuum region of the waveguide) are

Characteristic equation of TM^z modes ⟶ $$\varepsilon_r k_1 \sinh(k_1 d)\ \cos(k_2 h) - k_2 \cosh(k_1 d)\ \sin(k_2 h) = 0$$

$$E_y(y,z,t) = \frac{V_0\, k_1}{\sinh(k_1\, d)} \cosh[k_1\,((d+h)-y)]\ \cos(\omega\, t - \beta\, z)$$

$$k_1^2 \equiv \beta^2 - \omega^2 \mu_0\, \varepsilon_0 \qquad k_2^2 \equiv \omega^2 \mu_0\, \varepsilon_0\, \varepsilon_r - \beta^2$$

$$E_z(y,z,t) = -\frac{V_0\, k_1^2}{\beta\, \sinh(k_1\, d)} \sinh[k_1\,((d+h)-y)]\ \sin(\omega\, t - \beta\, z)$$

$$H_x(y,z,t) = -\frac{\omega\, \varepsilon_0}{\beta} E_y(y,z,t)$$

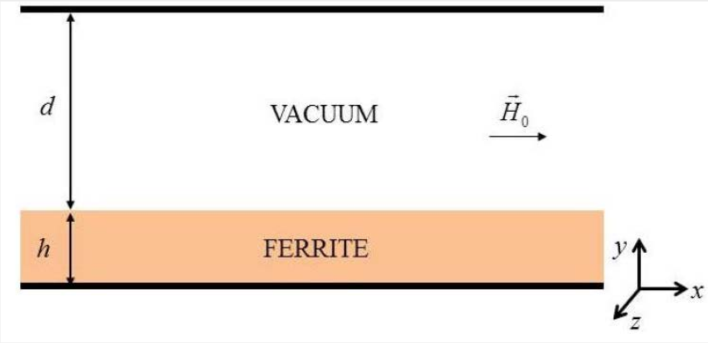
ε_0 is the vacuum dielectric permittivity
ε_r is the relative dielectric permittivity of the ferrite
d is the separation between plates
β is the propagation factor
V_0 is the amplitude voltage

$$V_0 = \int_h^{d+h} E_y(y,0,0)\,dy.$$

RF electromagnetic field computation

<u>Numerical Results:</u> Transversally parallel to the surface magnetized ferrite

The following partially filled ferrite waveguide was considered for multipactor simulations:



- Ferrite slab height, h = 3 mm
- Vacuum gap, d = 1 mm
- Saturation magnetization of the Ferrite, M_S = 1790 Gauss
- Relative dielectric permittivity of the ferrite, ε_r = 15.5
- SEY parameters for the upper metallic waveguide wall (silver): W_1 = 30 eV , W_{max} = 165 eV , δ_{max} = 2.22
- The same SEY parameters are chosen for the ferrite surface
- Three different magnetization field values are investigated , H_0 = 0 Oe, H_0 = 500 Oe, H_0 = 1000 Oe

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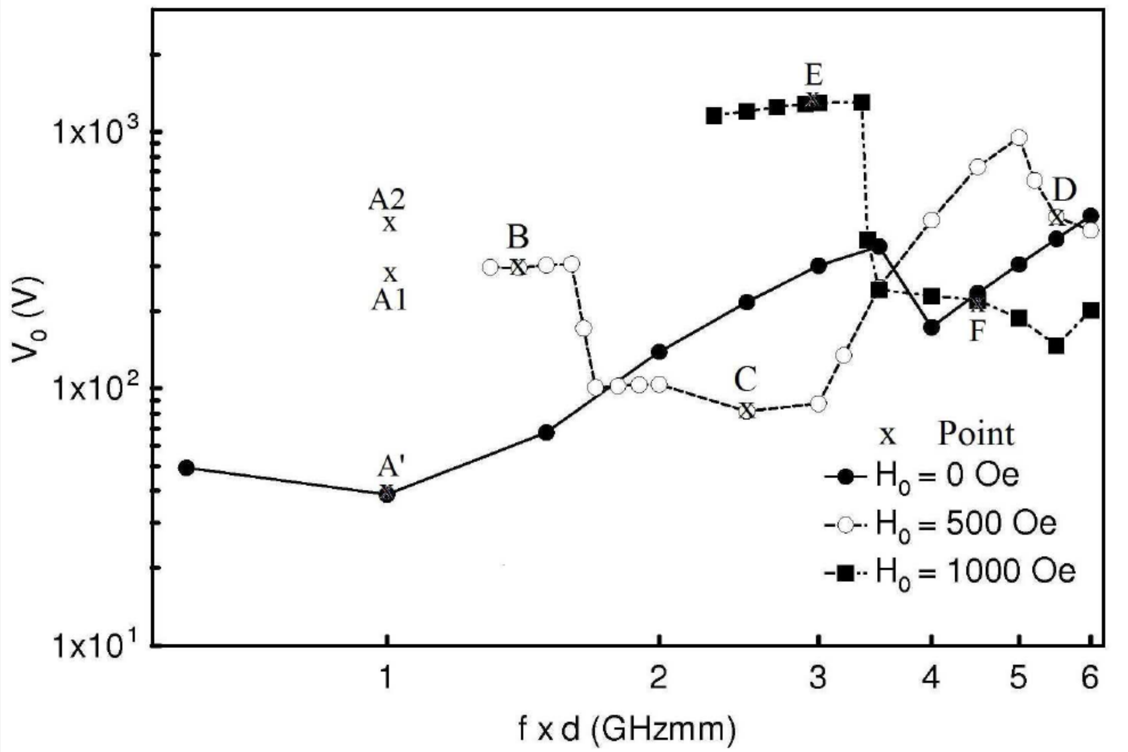
Simulations

Multipactor susceptibility chart for the parallalel-plate waveguide with the ferrite slab

- For H_0 = 0 Oe the ferrite exhibits no magnetic properties. Actually, the susceptibility chart is very similar to the classical metallic parallel-plate waveguide.
- For H_0 = 500 Oe and H_0 = 1000 Oe important variations in the multipactor voltage threshold regarding the Ho = 0 Oe case are found.
- The multipactor discharge cannot appear below 1.3 GHzmm when Ho = 500 Oe. The same occurs below 2.4 GHzmm when Ho = 1000 Oe.
- Electron trajectories are influenced by the ratio between the RF frequency and the cyclotron one.



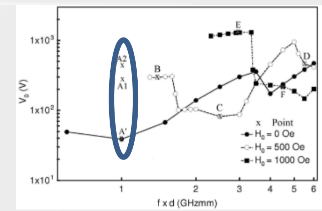
Multipactor voltage threshold as a function of the frequency gap value (gap remains fixed)

Cyclotron frequency $f_c = \frac{1}{2\pi}\frac{e}{m}B_0$

Simulations

Points A′, A1, A2

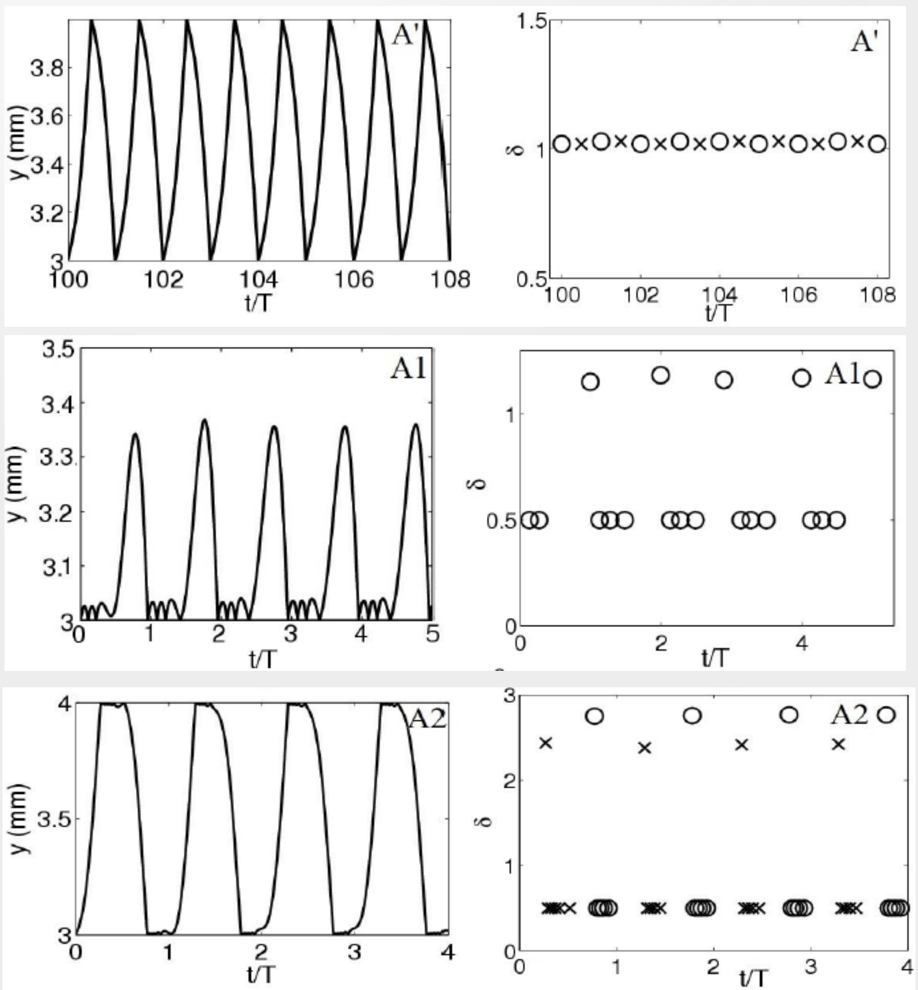
f x d = 1 GHzmm



H_o = 0 Oe

H_o = 500 Oe

H_o = 500 Oe

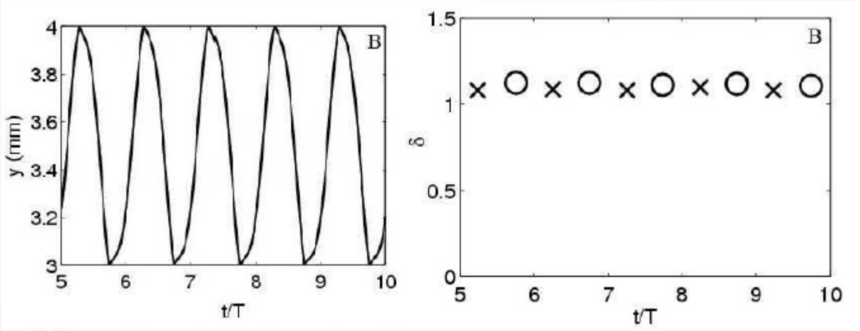


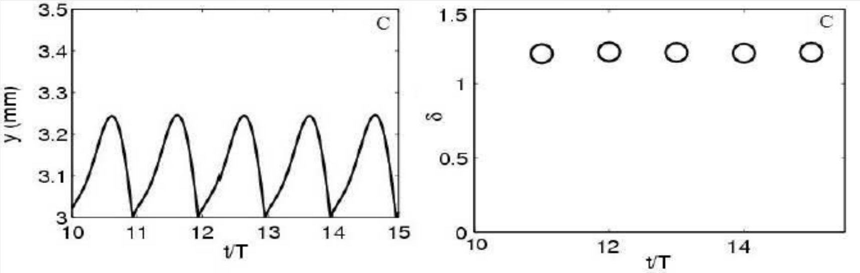
- Point A′. Double-surface multipactor discharge of order one. SEY slightly above the unity.
- Point A1. No multipactor discharge. Single-surface electron trajectories caused by the bending effect of the B_o field. The electron cannot synchornize with the RF electric field. Mean SEY below the unity.
- Point A2. No multipactor discharge. The RF voltage has increased regarding point A1. Now the electron can cross the gap despite the bending effect of the Bo field. However, no synchornization between electron and RF electric field is accomplished. Mean SEY below the unity.

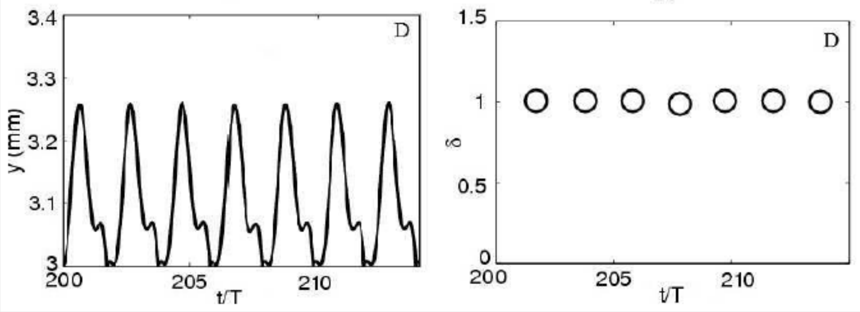
Simulations

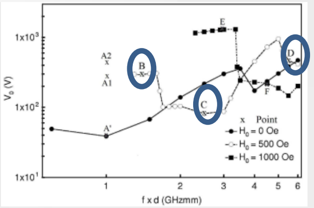
Points B, C, D

H_0 = 500 Oe









- Point B. Double-surface multipactor of order one. SEY slightly above the unity. The ratio between the RF frequency and the cyclotron one has increased regarding point A1 and A2. Consequently, the electron time flight is greater allowing the aparition of the order one.

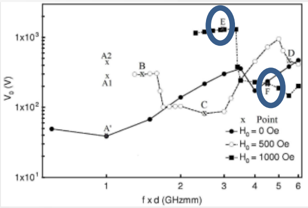
- Point C. Single-surface multipactor of order two. SEY slightly above the unitiy. RF voltage threshold has decreased regarding point B, due to the apparition of single-surface modes. Besides, this RF threshold value is below the Ho = 0 case.

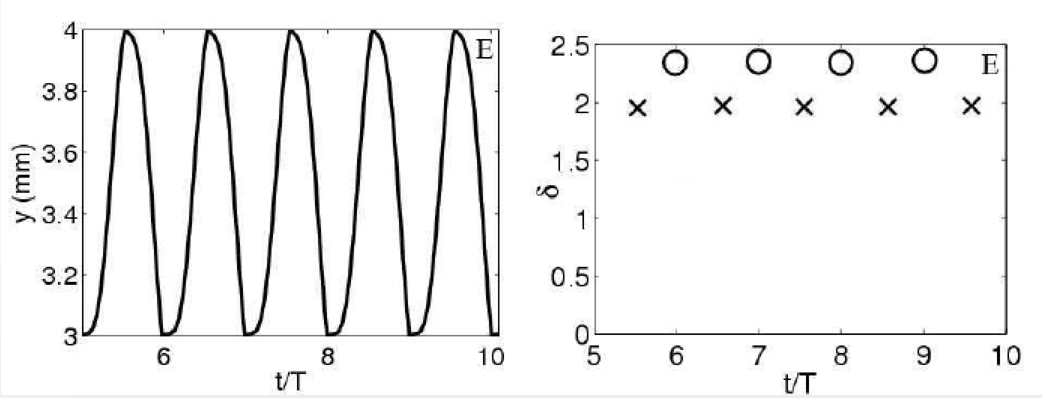
- Point D. Single-surface multipactor of order four. SEY slightly above the unity.

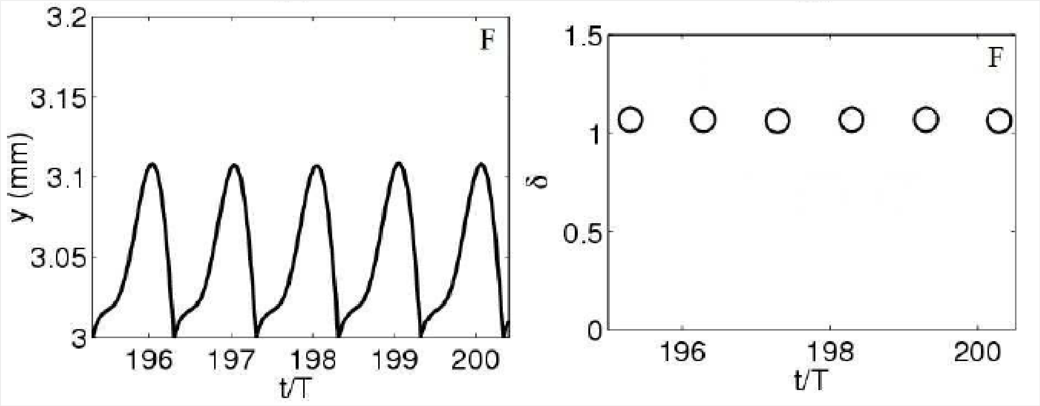
Simulations

Points E, F

H_o = 1000 Oe







- Point E. Double-surface multipactor of order one. SEY above the unity.
- Point F. Single-surface multipactor of order two. SEY slightly above the unity.
- There is a correspondence between points E, F and the points B, C; respectively. Actually, the multipactor curve shape for the case Ho = 1000 Oe is similar to the case Ho = 500 Oe but shifted towards higher frequency gap values. This fact can be explained in terms of the ratio between the RF frequency and the cyclotron one: similar values of this quotient imply similar multipactor resonances.

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Conclusions

The following conclusions can be outlined:

- An in-house multipactor simulation code has been developed to study the multipactor effect in parallel-plate waveguides partially filled with a ferrite slab.

- Multipactor susceptiblity charts have been computed exploring different values of the external magnetization field.

- The values of the multipactor RF voltage threshold obtained show important deviations from the classical metallic parallel-plate waveguide.

- Electron trajectories have been analyzed revealing the presence of both double and single surface multipactor regimes.

Publications

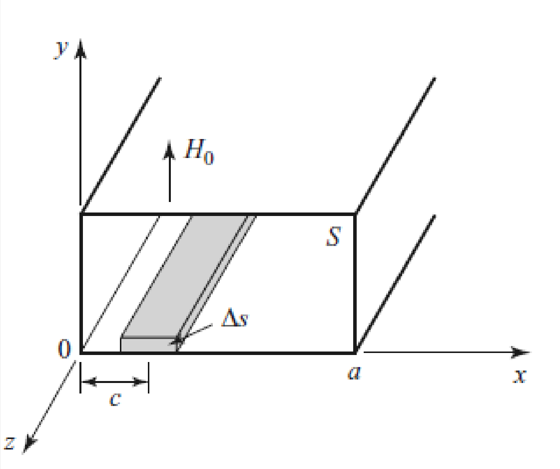
Some of the results shown in this presentation were published in:

- D. González-Iglesias, B. Gimeno, V. E. Boria, Á. Gómez, A. Vegas, "Multipactor Effect in a Parallel-Plate Waveguide Partially Filled With Magnetized Ferrite", *IEEE Transactions on Electron Devices*, vol. 61, no. 7, pp. 2552-2557, July 2014.

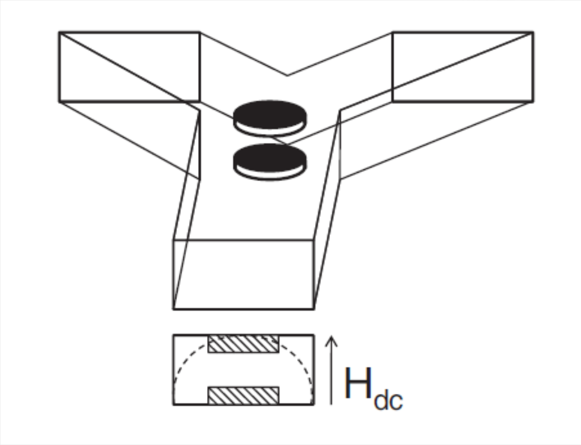
Future Lines

In a future work we will analyze the complementary case where the magnetization field is oriented perpendicularly to the ferrite slab.

This configuration will be useful to the understanding of some kind of high-power circulators and isolators



H-plane, partial-height slab resonance isolator[1]



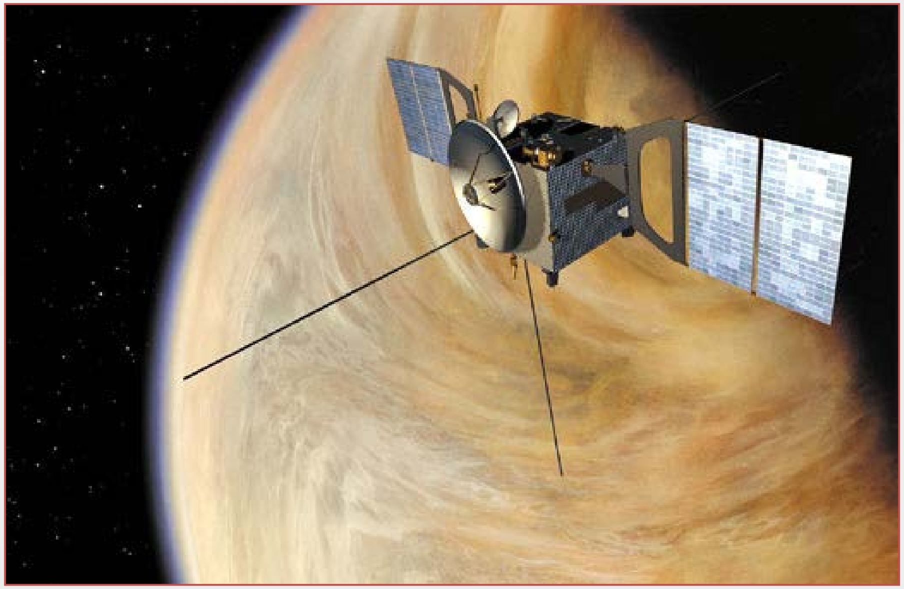
H-plane junction of waveguide circulator[2]

[1]D. M. Pozar, Microwave Engineering, 4th ed. New York, NY, USA: Wiley, 2012.

[2] A New dual-band high power ferrite circulator, H. Razavipour, R. Safian, G. Askari, F. Fesharaki and H. Mirmohamad Sadeghi, Progress In Electromagnetics Research C, vol. 10, 15-24, 2009.

Acknowledgement

This work was supported by the European Space Agency (ESA) under "Novel Investigation in Multipactor Effect in Ferrite and other Dielectrics used in high power RF Space Hardware", Contract AO 1-7551/13/NL/GLC, and partially by the Spanish Government, under the Research Project TEC2013-47037-C5-4-R.



We are open to cooperate with all of you.

Thanks a lot for your attention.

III. Multipactor simulation algorithm

MONTE-CARLO ALGORITHM: Effective electron model

- This model consists of the tracking of the individual trajectories of *M* effective electrons as well as its accumulated electron population.

- Each effective electron will gain or lose charge and mass after every impact with the device walls depending on the Secondary Electron Yield δ (SEY) value at the impact

Accumulated electron population due to the *i-th* effective electron after impacting at time *t* → $N_i(t+\Delta t) = \delta N_i(t)$

- The electron total population in the device may be obtained by adding the accumulated population of each of those effective electrons

Total electron population → $N(t) = \sum_{i=1}^{M} N_i(t)$