Predictions of microwave breakdown in rf structures

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Outline of the Presentation

1. Introduction (motivation and brief description of the breakdown phenomenon).
2. Electron interaction with microwave field (rough estimates of parameters which are dangerous from the breakdown point of view).
3. Basic theories of multipactor and corona breakdown.
4. Simplified models and their limitations.

(continuation)

5. Detailed numerical simulations are necessary for accurate predictions of the breakdown threshold.
6. Demonstration of the software developed to simulate the corona and the multipactor effects inside rf filters.
7. Conclusions.
Introduction.

Progress in communication systems

- Increase in power and frequency bandwidth
- Design of more compact devices
- More complicated geometries & Higher intensity of rf field
- Higher risk of breakdown & More complicated prediction of breakdown threshold

Microwave breakdown phenomena

**Vacuum conditions:**
\[ l_0 \gg L \]
- Length of electron free path
- Gas pressure \( p \) [Torr]

**Gas environment:**
\[ l_0 \ll L \]
- Size of device

**Vacuum discharge** (multipactor effect)
- Secondary electron emission from the walls

**Gas discharge** (corona effect)
- Electron impact ionization of neutral gas molecules

\[ l_0 [cm] \approx \frac{2 \cdot 10^{-3}}{p [\text{Torr}]} \]
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Microwave breakdown phenomena

**Vacuum discharge**
(multipactor effect)

**Gas discharge**
(corona effect)

**Necessary condition**

There should be electrons with energy $W_e$

- $W_e > W_1 \approx 20 \div 100 \text{eV}$
- $W_e > W_i \approx 10 \div 20 \text{eV}$

first cross-over point of SEY curve

ionization energy

**Study of electron interaction with microwave field**

Electron acceleration in microwave field under vacuum conditions

\[
\text{max } W_e \leq 4 \cdot W_\omega \propto \left( \frac{E_\omega}{\omega} \right)^2
\]

\[
W_\omega = \frac{mV_\omega^2}{2}
\]

\[
V_\omega = \frac{eE_\omega}{m\omega}
\]

Necessary distance:

\[
\Lambda = \pi V_\omega / \omega
\]

Operation of a vacuum rf device is potentially dangerous from the multipactor point of view when

\[
4W_\omega > W_1
\]

\[
L > \Lambda
\]
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Electron heating in microwave field in the presence of collisions with neutral molecules

In gaseous environment the interaction of electrons with microwave field depends on 2 extra parameters:

**Collision frequency** $\nu$

$\nu \propto p$  

*gas pressure*

in air:

$\nu [s^{-1}] = 5 \cdot 10^9 \cdot p [\text{Torr}]$

**Energy loss factor** $\delta$

$\delta$ depends on the sort of gas

$\delta \approx (1 \div 3) \cdot 10^{-3}$  

for gases with single-atom molecules

$\delta \approx (1 \div 3) \cdot 10^{-2}$  

for gases with multi-atom molecules

---

**rarefied gas:** $\nu << \omega$

**dense gas:** $\nu >> \omega$

average gain of electron energy between two collisions:

$\langle \Delta W_e \rangle \approx W_\omega$

$\langle \Delta W_e \rangle \approx W_\omega \cdot \left( \frac{\omega^2}{\nu^2} \right)$

$\langle W_e \rangle \approx \frac{W_\omega}{\delta} \left( \frac{\omega^2}{\omega^2 + \nu^2} \right)$

$\langle W_e \rangle \approx \frac{W_\omega}{\delta} \left( \frac{\omega^2}{\omega^2} \right)$

$\langle W_e \rangle \approx \left( \frac{W_\omega}{\delta} \right) \cdot \left( \frac{\omega^2}{\nu^2} \right)$

**Operation of rf device under gas environment is potentially dangerous from the breakdown point of view if**

$\langle W_e \rangle > 2 \div 5 \text{ eV}$

$L > \frac{l_0}{\sqrt{\delta}}$
Evolution of electron density $n$ is governed by ionization, attachment and diffusion processes:

$$\frac{\partial n}{\partial t} = \nabla^2 (Dn) + (\nu_i - \nu_a)n$$

$D$ is diffusivity of free electrons in a gas

$\nu_i$ is the frequency of impact ionization of neutral particles

$\nu_a$ is the frequency of electron attachment to neutral particles

$\nu_i$ and $\nu_a$ depend on average electron energy and are proportional to gas pressure when $\langle W_e \rangle$ is fixed.

$D \propto \frac{1}{p}$ when $\langle W_e \rangle$ is fixed

Boundary conditions: $n = 0$ at solid surface

Breakdown criterion: an exponential increase of electron density in time

$n \propto \exp(\gamma t)$

$\gamma > 0$ in case of CW operation

$\gamma > 20/\Delta t$ in pulse operation regime with pulse duration $\Delta t$
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Simplified model of microwave gas breakdown

The simplified model of gas breakdown is based on the approximation of spatially uniform distribution of microwave field intensity.

Breakdown criterion: \( \gamma > \frac{20}{\Delta t} \)

\( \gamma = v_i - v_a - v_d, \quad v_d = D/L^2 \)

Estimate of electron loss rate due to diffusion.

Increase in diffusion losses since \( D \propto 1/p \)

Paschen curve

\( E_\omega \propto p \) since \( \langle W_e \rangle \propto (E_\omega/v)^2 \)

The main limitation of the simplified model

The accuracy is not high enough especially in systems with complicated geometry.

The only way for reliable predictions of the breakdown threshold is to solve numerically the diffusion problem for the electron density.
Basic theory of multipactor discharge

In contrast to the gas discharge theory, the theory of multipactor considers the motion of separate electrons in the microwave field:

\[
m \frac{d^2 \mathbf{r}}{dt^2} = e \mathbf{E} + \frac{e}{c} \left[ \frac{d \mathbf{r}}{dt} \times \mathbf{H} \right]
\]

**Boundary conditions:**
Collisions of an electron with a solid surface are accompanied by emission of new secondary electrons. The number of secondaries depends on the energy of the primary electrons.

**Secondary emission yield curve**

**Necessary condition:**
There should be electrons with energy
\[ W_e > W_1 \]

**Multipactor criterion:**
an exponential increase of average electron number in time
\[ N \propto \exp(\gamma t) \]
\[ \gamma > 0 \]
The simplified model of multipactor is based on the resonance concept.

The multipactor is related to such electron trajectories which are repeated periodically in time.

Main requirements:
- the resonance trajectory must be stable with respect to small deviations of initial time and position.

Cross-section of rectangular waveguide

A spread in initial velocities of the secondary electrons is neglected.

Considerable reduction of prediction accuracy for resonances of high order.

A typical situation in systems with complicated geometry is spatial instability of resonance trajectories.

The resonance trajectory completely changes character.

The only way to obtain reliable predictions of the multipactor threshold is extensive numerical simulations.
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Requirements on numerical algorithms

Main requirements on software for breakdown simulations

Corona
• Accurate calculations of the spatial distribution of the rf electric field intensity
• Accurate solution of the diffusion problem for the electron density

Multipactor
• Accurate calculations of the rf electric and magnetic field strengths
• Calculations of electron trajectories taking into account a spread of electron initial velocity and the action of the rf magnetic field on the electron motion
Model space configuration:

- rectangular configuration;
- the filter is symmetric relative to the plane $YZ$;

Assumptions:
The filter walls are assumed to be perfectly conducting (i.e. the tangential component of the electric field is assumed to be zero on the walls).
The entrance and exit cross-sections of the filter are supposed to be nonreflecting.

Variable filter parameters:
- number of sections;
- height $X$, length $Z$ of each section;
- width $Y$ (the filter dimension along $y$ axis)

Variable field parameters:
- field frequency $f$ [GHz];
- input wave polarization
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Software SEMA. Input wave polarization.

**Quasi two-dimensional cases:** the structure of the electromagnetic field is fixed in the y-direction

**TE\(_{n0}\)-mode** \((n = 1, 3, 5, \ldots)\)

\[
E_{0y} = \bar{E}_{0y} \cos\left(\frac{n\pi x}{a}\right)
\]

inside the filter: \(E_x, E_z = 0\)

\(E_y\) does not depend on \(y\) coordinate

**TE\(_{n1}\)-mode** \((n = 0, 2, 4, \ldots)\)

\[
E_{0x} = \bar{E}_{0x} \cos\left(\frac{n\pi x}{a}\right) \cos\left(\frac{\pi y}{b}\right)
\]

\[
E_{0y} = \frac{nb}{a} \bar{E}_{0x} \sin\left(\frac{n\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right)
\]

inside the filter:

\(E_y \propto \sin(\pi y/b)\)

\(E_x, E_z \propto \cos(\pi y/b)\)
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Simulation of the diffusion problem

Variable parameters:

- **Input Power** [W]
- **Gas Pressure** \( p \) [Torr]
- **Sort of gas**:
  - (i) Air
    \[
    D = 10^6/p; \quad v_a = 6 \cdot 10^4 \cdot p; \quad v = 5 \cdot 10^9 \cdot p
    \]
    \[
    v_i = 4 \cdot 10^7 \cdot p \left( \frac{E_{\text{eff}}}{100p} \right)^{16/3}
    \]
    \[
    E_{\text{eff}} = \frac{E^2}{2} \cdot \frac{v^2}{v^2 + \omega^2}
    \]
  - (ii) He, Ne, Ar, Kr, Xe, \( N_2, O_2, H_2, Cl_2, F_2, HCl, CF_4, SiH_4, CH_4, SF_6 \)

He, Ne, Ar, Kr, Xe, \( N_2, O_2, H_2, Cl_2, F_2, HCl, CF_4, SiH_4, CH_4, SF_6 \)


\[
\frac{\partial n}{\partial t} = \nabla^2 (Dn) + (v_i - v_a)n
\]

Initial and boundary conditions:

- \( n = 1 \) in the whole volume of the filter at \( t = 0 \);
- \( n = 0 \) on the metal walls;
- \( \partial n/\partial z = 0 \) in the entrance and exit filter cross sections.

FDTD scheme is used for simulation of the diffusion problem
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Calculation of electromagnetic problem

Numerical calculations of electromagnetic field inside a filter are based on mode-expansion algorithm. The electromagnetic field in a filter section can be presented as a sum of Eigen modes of this section.

\[
E_\perp = \sum_n \left\{ A_n^+ (z) + A_n^- (z) \right\} E_n
\]

amplitudes of the waves:
\[
A_n^+ = A_n^{\text{out}} (z_s +) \exp(ik_n(z - z_s)) \\
A_n^- = A_n^{\text{in}} (z_s +) \exp(ik_n(z_s - z))
\]

\(z_s \leq z \leq z_{s+1}\)

\(k_n\) are propagation constants

Mode-expansion algorithm

The complete set of equations for the mode amplitudes \(A_n\) includes:

1) propagation equations:
\[
A^{\text{in}}(z_{s+1} -) = \hat{P}_+ A^{\text{out}}(z_s +) \\
A^{\text{in}}(z_s +) = \hat{P}_- A^{\text{out}}(z_{s+1} -)
\]

2) transmission-reflection equations:
\[
A^{\text{out}}(z_s +) = \hat{R}_+ A^{\text{in}}(z_s +) + \hat{T}_+ A^{\text{in}}(z_s -) \\
A^{\text{out}}(z_s -) = ...
\]
Matrices of propagation $\hat{P}_+$, $\hat{P}_-$ are known.

In particular, $\hat{P}_+ \leftrightarrow \{\exp(i h_n (z_{s+1} - z_s))\}$

Matrices of reflection $\hat{R}_+$, $\hat{R}_-$ and transmission $\hat{T}_+$, $\hat{T}_-$ can be calculated using:

1) the continuity conditions for electromagnetic field components in the junction-planes of filter sections;

2) the boundary conditions for the mode amplitudes:

\[ A^{in}(z_1 -) = A^{out}(z_1 +) = A_{input \_ wave} \]

\[ A^{in}(z_{N+1} +) = A^{out}(z_{N+1} -) = 0 \]

Advantages of the mode-expansion algorithm

The advantages of the mode-expansion algorithm compared with grid-methods of electromagnetic calculations:

1) no problem of scale matching of grids in the junction-planes of the filter sections;

2) no need for numerical calculations of electromagnetic field inside filter sections since analytical solutions are available there.

The code based on the mode-expansion algorithm demonstrates **high computational speed** & **high accuracy of calculations**
Additional advantages of the software SEMA:

1) Visualization of electric field distribution
2) The possibility to chose one (or several) filter section for calculations of the diffusion problem.

It significantly reduces the computing time for calculating the electron avalanche growth (if any) and increases the accuracy of these calculations.

The software has been tested in different manners.

1) Electrodynamic part. Calculation of dispersion matrix: parameters $S_{11}$, $S_{12}$

Courtesy of Alcatel Alenia Space SPAIN

ideal circuit simulation (CNES)
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Software SEMA. Breakdown simulations.

2) Breakdown simulations. 
Comparison with experimentally observed data for breakdown thresholds.

In particular, measurements of corona breakdown was made in a waveguide switch used at CNES: the threshold at the pressure $12 \text{ hPa}$ (~9 Torr) was found to be $410 \text{ W}$

The simulation result:

10 Torr, 410 W – breakdown!
10 Torr, 400 W – no breakdown

Courtesy of Alcatel Alenia Space FRANCE

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Software MulSym. Multipactor simulations.

A software MulSym for simulations of multipactor problem in a rectangular filter has been developed. It is based on the Monte-Carlo algorithm. The electric field distribution in the filter is computed by SEMA. MulSym makes it possible the study the development of multipactor discharges in real time in different filter sections. The software takes into account:

1) a spread of initial velocities of secondary electrons;
2) the action of the rf magnetic field on the electron motion.

The software MulSym is currently being tested.
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Software SEMA. Demonstration.

Setting of filter parameters. Example.

Test of “CNES-filter”
Frequency = 11.7 GHz
Simulation of diffusion problem in the fourth resonator

Air:
- Power = 32 W;
- Pressure = 8 Torr;
- Breakdown!

30 W & 8 Torr;
No breakdown!

Experimental result:
threshold level -- 30 W

Courtesy of Alcatel Alenia Space SPAIN
Conclusions.

- Classical understanding and modelling of corona and multipactor breakdown is not sufficient for accurate prediction of breakdown thresholds in many modern rf structures and communication scenarios.

- **Main complications are caused by:**
  - (i) electric field inhomogeneity (complicated geometries);
  - (ii) time varying electric field (multi-carrier operation).

- **Breakdown predictions require:**
  - Finding the electric & magnetic fields in the rf device.
  - Solving for the evolution of the electron density in these fields.

Present work.

- **Numerical code have been developed for:**
  - (i) finding the electric and magnetic fields in wave guide configurations built on “rectangular” elements;
  - (ii) determining the evolution of the electron density in the corresponding fields.

  Corona discharges (the diffusion equation)
  Multipactor discharges (electron trajectories)
Present work.

• The codes have been applied to study:
  (i) corona breakdown in different filters and around sharp corners and wedges
  (ii) multipactor in rectangular wave guides, wave guides with irises, coaxial lines, etc.
  (iii) multipactor in multi-carrier operation

The presented work represents a significant step forward in the predictive modelling of breakdown in geometrically complicated rf devices and for multi-carrier operation scenarios.