Microwave multipactor breakdown in open two-wire transmission systems

Joel Rasch*, D. Anderson*, V. E. Semenov, E. Rakova, J. F. Johansson, M. Lisak* and J. Puech

*Chalmers University of Technology

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Outline

- Multipactor, a short review
- The Helix antenna
- Simplified two-wire system
- The simplified theoretical model
- Simulations
- Comparisons between simulations and theory
- Conclusions

Multipactor, a short review

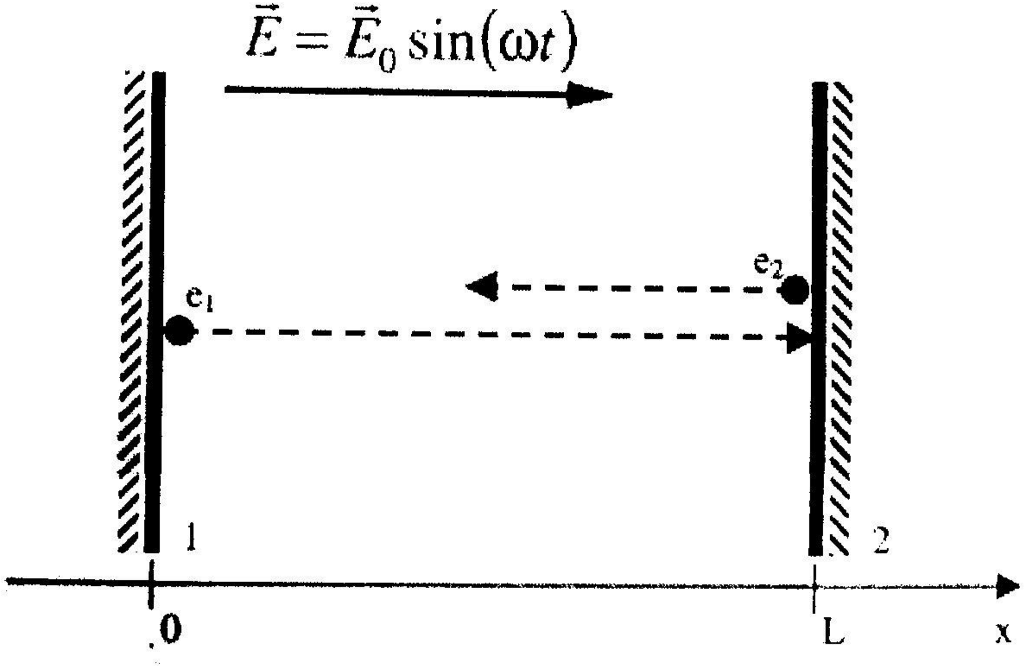
- Multipactor, or multipaction – the exponential increase in the number of free electrons due to electrons gaining energy from the EM-field and causing secondary electron emission upon impact.
- Occurs in vacuum, or near vacuum in high power RF devices; waveguides, antennas, dielectric windows, etc.
- Causes a number of problems in microwave systems, mainly noise, changing device impedance, heating device walls, lengthening device conditioning time, etc.

Multipactor, a short review

- Poses a risk in any vacuum system with strong electric fields of high frequency.
- Particle accelerators, dielectric windows for high power microwave devices (magnetrons, gyrotrons), satellite radio systems etc.
- Satellite systems are a big concern, due to extreme conditions, limited testing availability, high costs, and the impossibility of altering a system in orbit

Multipactor, a short review

- **Classical case of two parallel infinite metal plates**



Multipactor, a short review

- The electrons will be accelerated by the electric field and their motion can be described by

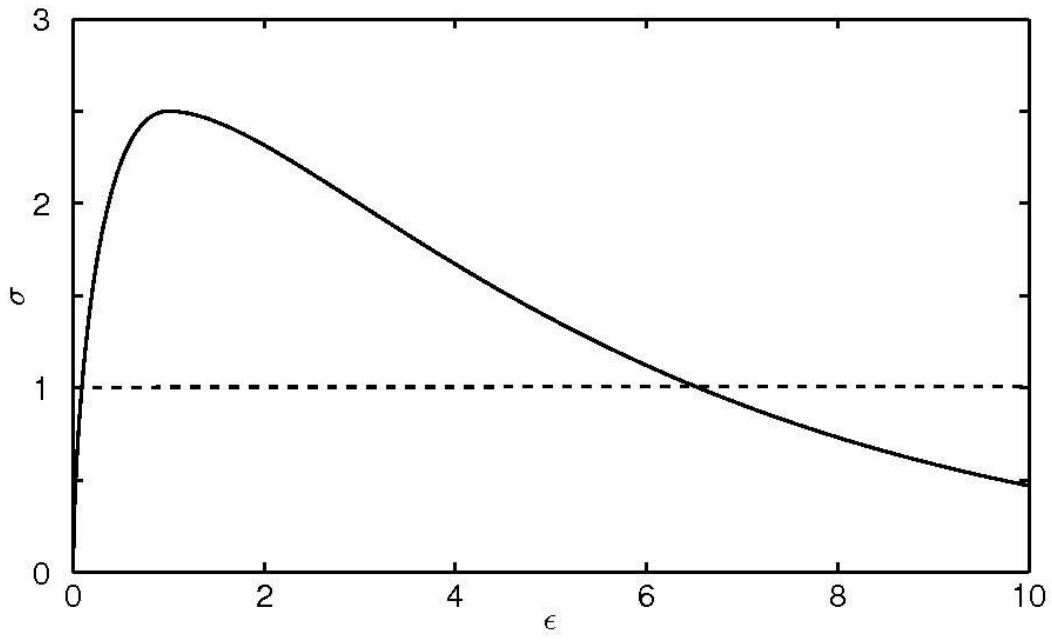
$$v(t) = v_{\omega} \cos(\omega t) + v_d$$

- where $v_{\omega} = \dfrac{eE_0}{m\omega}$

- and $v_d = v_e + v_{\omega} \cos(\omega t_e)$

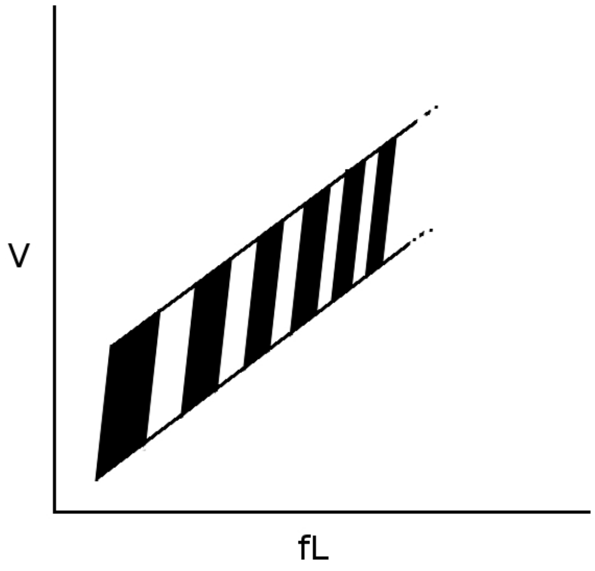
Multipactor, a short review

- **The secondary emission yield depend on the impact energy as**



Multipactor, a short review

- The basic criterion for multipactor is sufficient impact energy to produce a net gain in electron number between successive impacts
- In parallel plates geometry we also need resonance. Electrons should impact the other wall at the exact opposite phase
- Summarized in Hatch-Williamson diagram



Multipactor, a short review

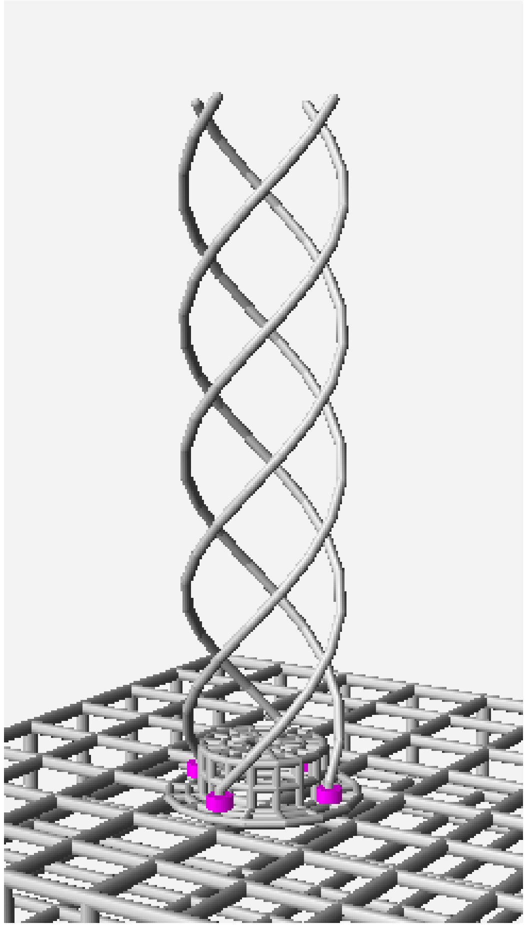
- The parallel plates multipactor scenario have dominated research since the beginning with Farnsworth in 1934
- However, for large gap widths, the spread in emission velocity and angle will blur the resonance zones, making sufficient electron energy the most important factor.

$$\sigma(v_{impact}) > 1$$

- It is not obvious how to generalize the knowledge from the parallel plates case to more complicated geometries, the major complication being inhomogeneous electric fields.

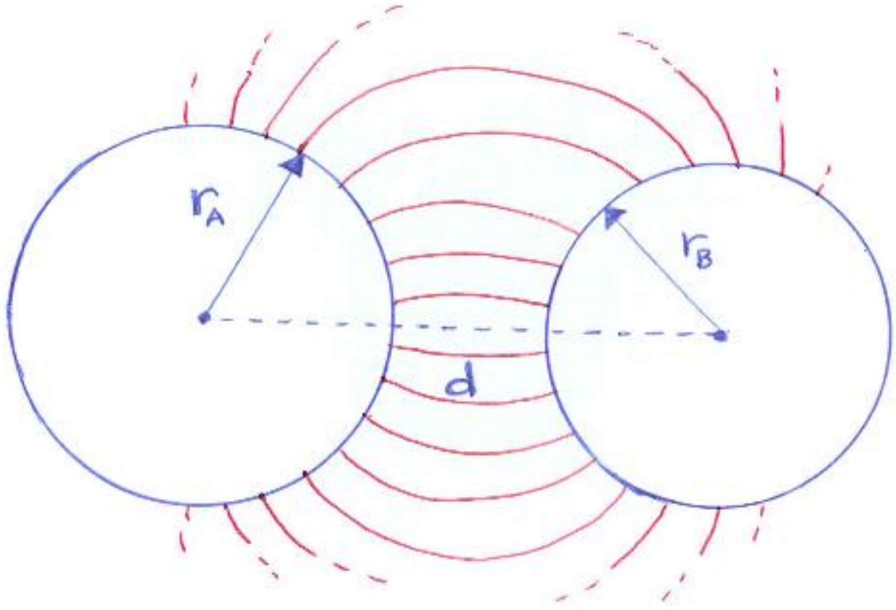
The Helix antenna

- A helically wound antenna with four wires used for satellite communications
- The level of complexity compared to the parallel plates is large
- As of now, the ECSS states that the parallel plates model recommendations should be used.
- However, electron losses due to geometry should be considerable



Simplified two-wire system

- As a first step in the evaluation of the multipactor risk in the helix system we consider two parallel infinite cylinders.
- The EM-field in this system is known exactly!!



Simplified two-wire system

- The model retains the most important qualitative features compared to the full helix system
  - Curved surface geometry
  - Inhomogeneous field
  - Open structure, allowing electrons to be lost

The simplified theoretical model

- The theoretical model we use is a simplified, average approach which includes
  - Losses due to geometrical spreading
  - Ponderomotive acceleration and deceleration of electrons, for cylinders of unequal radii
  - Averaging of the electron impact speed to get the average secondary emission yield
- For this approach to be valid, the gap between cylinders must be large, i.e. electrons complete many cycles during passages.

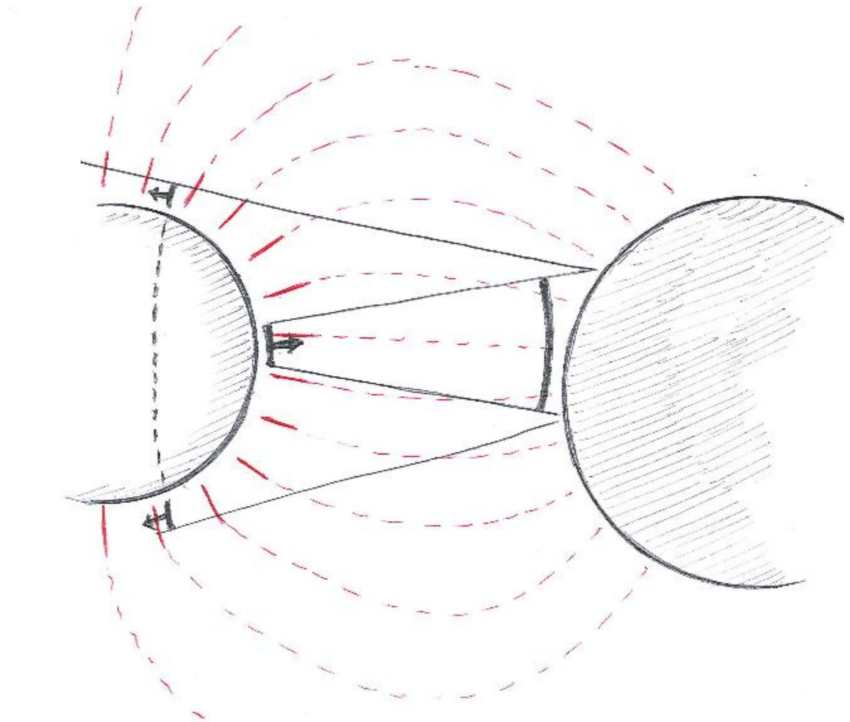
The simplified theoretical model

- In ”realistic” systems this requirement is met
- The full details are available in our recent paper J. Rasch et al., ”Microwave multipactor between two cylinders”, IEEE Trans. Plasma Sci. 38, 1997 (2010)

The simplified theoretical model

- The geometrical losses occur due to two facts:
  - The electric field is normal to the cylinder surfaces
  - The main electron acceleration occurs directly after emission
- This causes the electrons to drift outwards from the cylinder surfaces, causing a dilution of electron density

The simplified theoretical model



- **Mathematically**

$$\sigma^2{}_{effective} = \frac{\sigma^2(v_{impact})}{(1+d/R_A)(1+d/R_B)}$$

The simplified theoretical model

- There is a minimum radius, below which multipactor should be impossible. It occurs when the effective maximum secondary emission yield (SEY) equals unity

$$1 = \frac{\sigma^2{}_{\max}}{(1 + d/R_A)(1 + d/R_B)}$$

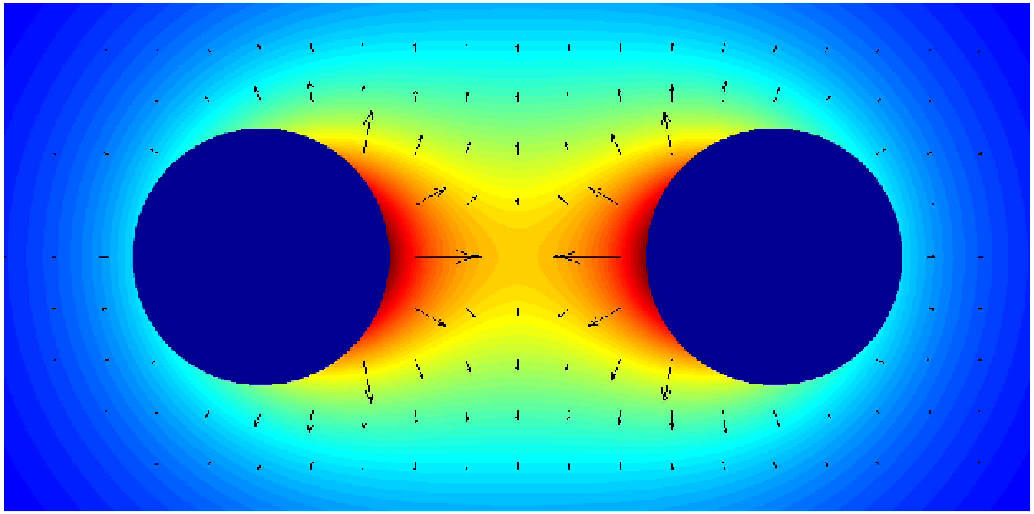
- The geometrical dilution should be very important for realistic systems
- For example, an 8 GHz antenna has a gap width of 3.8 mm, and cylinder radii of 0.6 mm, meaning that the maximum SEY has to be 7.3. Unlikely for any material used in space equipments.

The simplified theoretical model

- **The second effect we include is the pondero-motive force.**
- **The average force experienced by oscillating charges in inhomogeneous fields.**

$$\overline{F} = -\frac{\nabla v_\omega^2}{4}$$

$$v_\omega = \frac{eE_0}{m\omega}$$



The simplified theoretical model

- The ponderomotive force will cause an extra electron dilution in the tangential direction, but it is small, and we neglect it
- More important is the change in electron drift speed.
- Conservation of energy in this case means

$$v_{d1}^2 + \frac{v_{\omega 1}^2}{2} = v_{d2}^2 + \frac{v_{\omega 2}^2}{2}$$

The simplified theoretical model

- The maximum drift velocity is

$$v_{d,\max} = v_{\omega} + v_{e} \approx v_{\omega}$$

- Thus, electrons traveling from field 1 to field 2 will stop when

$$v_{d,\max}^{2} + \frac{v_{\omega 1}^{2}}{2} = \frac{v_{\omega 2}^{2}}{2} \Leftrightarrow E_2 = \sqrt{3} E_1$$

- Since the field strength is determined by the geometry, this limits the maximum difference in radii for which two sided multipactor may be possible

The simplified theoretical model

- The same phenomena appears in coaxial waveguides, limiting the radii ratio for double sided multipactor to

$$\frac{R_{outer}}{R_{inner}} < \sqrt{3}$$

- The limits for the radii in the two wire system are similar, but more complicated

The simplified theoretical model

- The third assumption: the impact speed can be averaged and used in the formula for the secondary emission coefficient.
- The probability for impact with a certain speed is the distance traveled with that speed divided by the total distance traveled, i.e.

$$dP_{impact}(v) = \frac{v\,dt}{\int_0^T v(t)\,dt}$$

The simplified theoretical model

- **Thus**

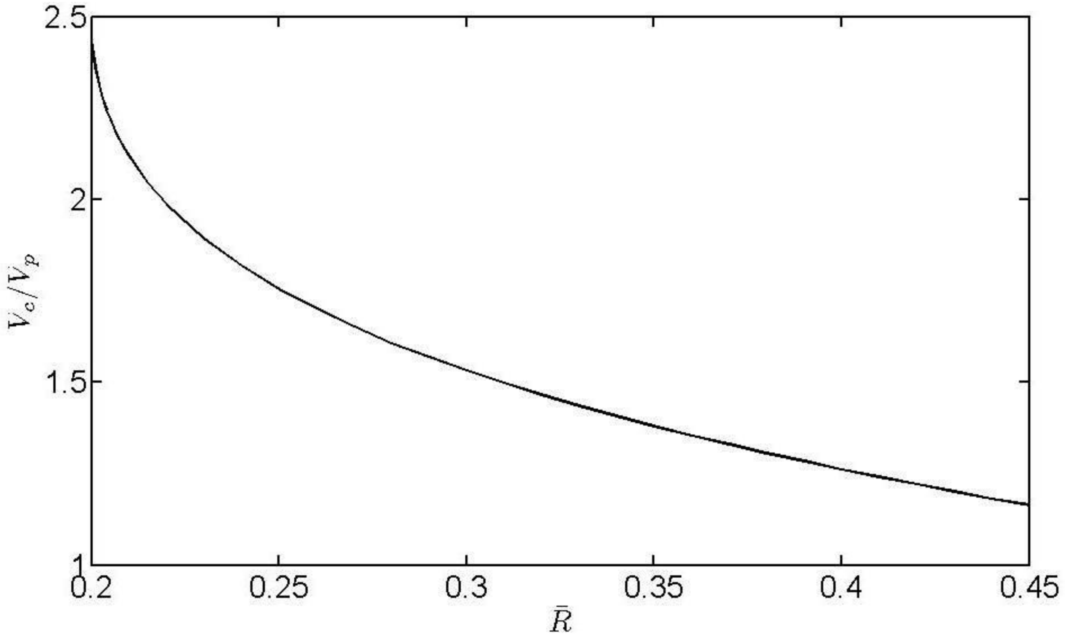
$$< v_{impact} >= \int_0^T v(t)dP(t) = \frac{\int_0^T v^2(t)dt}{\int_0^T v(t)dt}$$

- **For cylinders of equal radii, we consider only the most energetic electrons,**

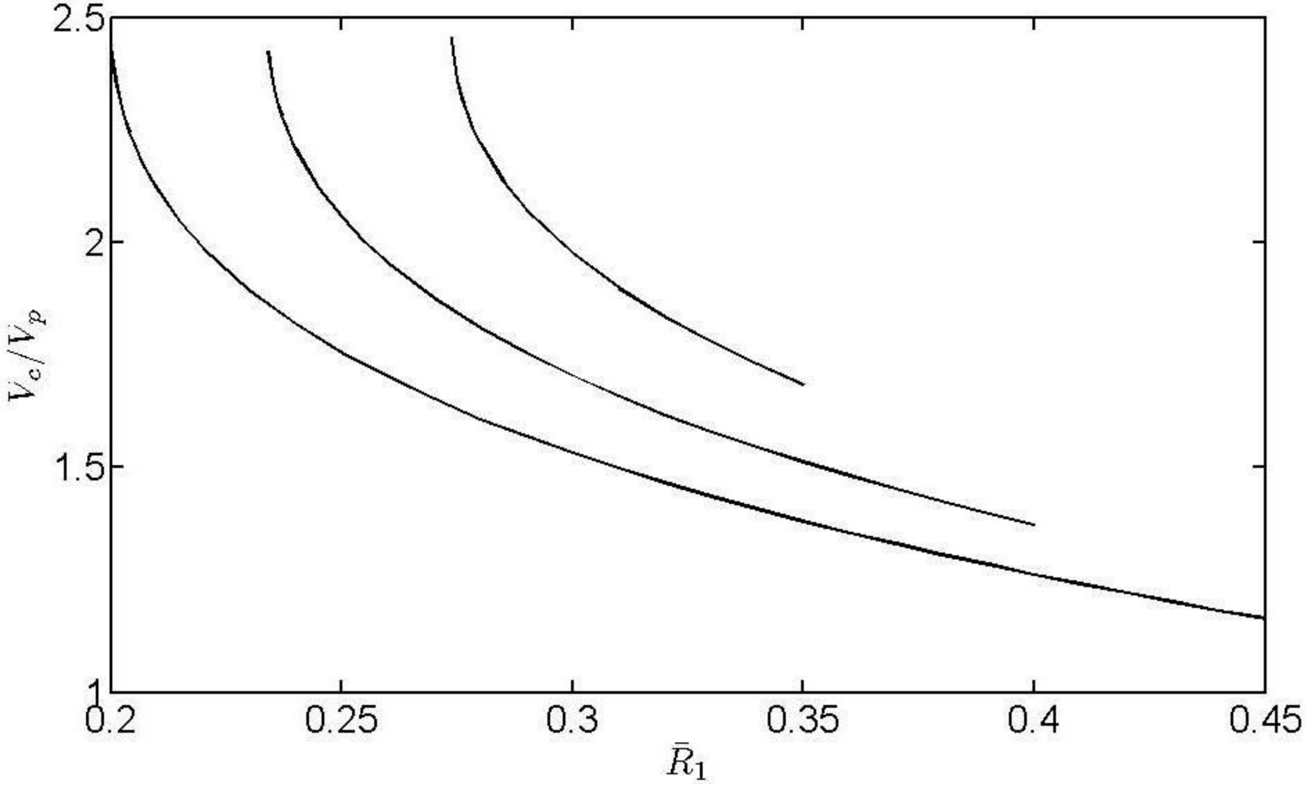
$$< v_{impact} >= \frac{3}{2} v_{\omega}$$

The simplified theoretical model

- **Putting these three ingredients together, using the formulas for the field, and using the Vaughan model for the SEY for silver (SEY_max=2.22), we can draw some nice figures**



The simplified theoretical model



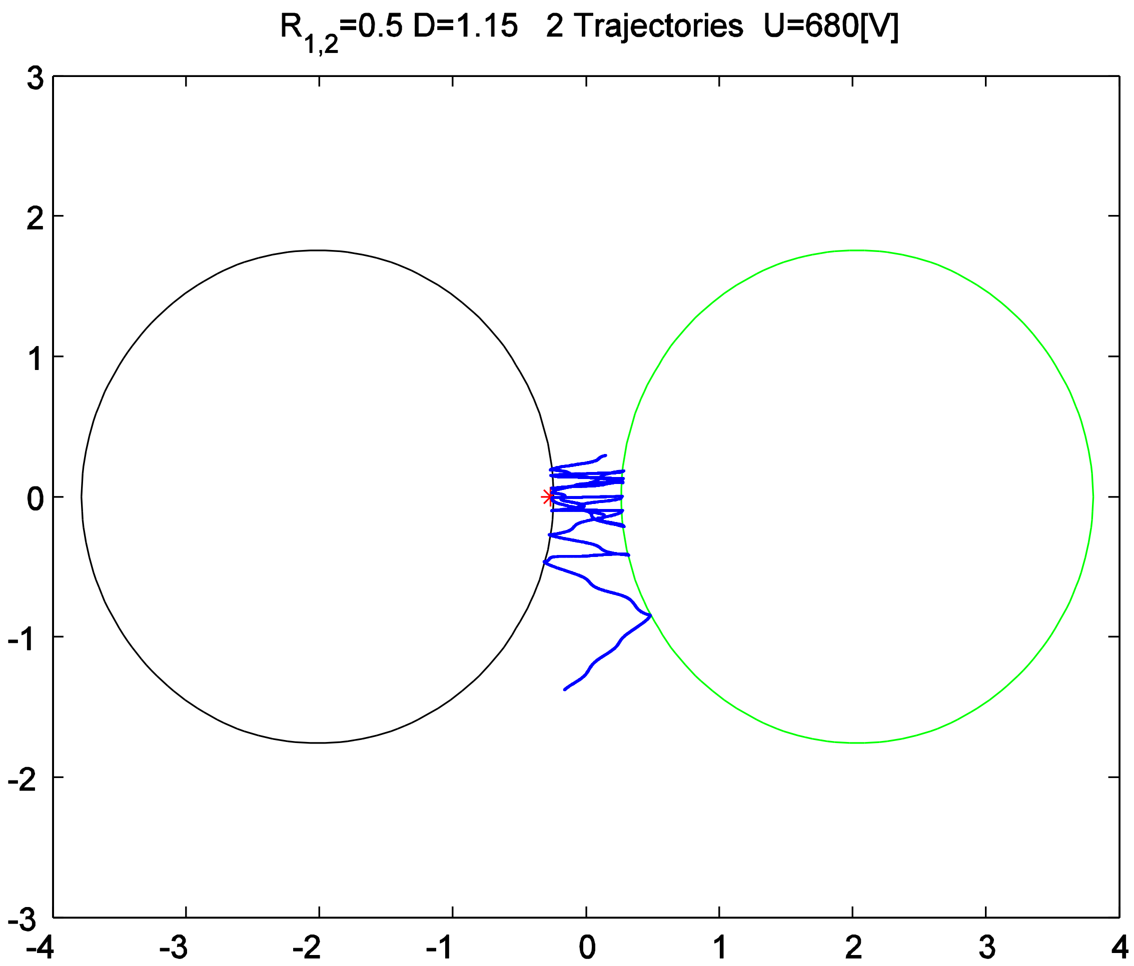
The simplified theoretical model

- **The main result from the theoretical model is the fact that there is a smallest radius for every system, under which two-sided multipactor is impossible, under the assumptions of the model!**

Simulations

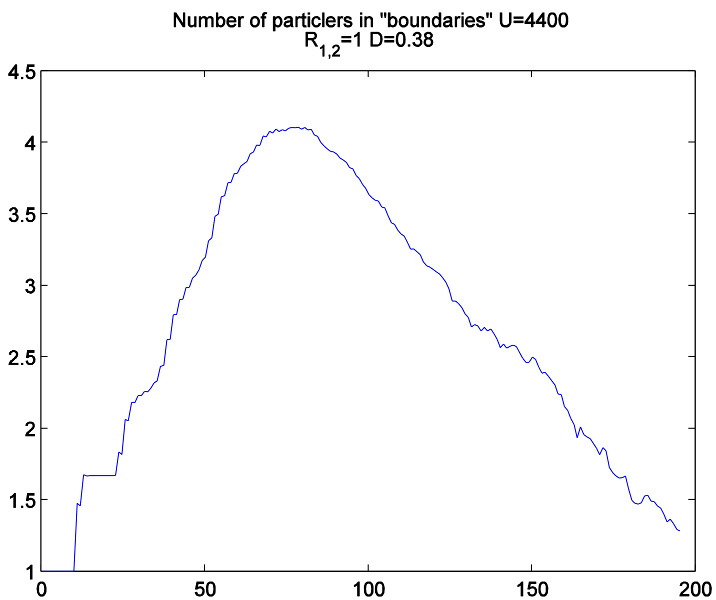
- To test the predictions of the theoretical model, a Monte Carlo code was developed.
- Cylinders of equal radii where considered, where the gap between the cylinders was varied
- The electron emission energy was 3 eV, and distributed evenly over angle with respect to the cylinder surfaces
- Electrons traveled in bunches, and upon every impact, the number of electrons in the bunch was multiplied with the SEY for the bunch velocity
- The material used was silver with SEY_max=2.22, and first cross over velocity 30 eV.

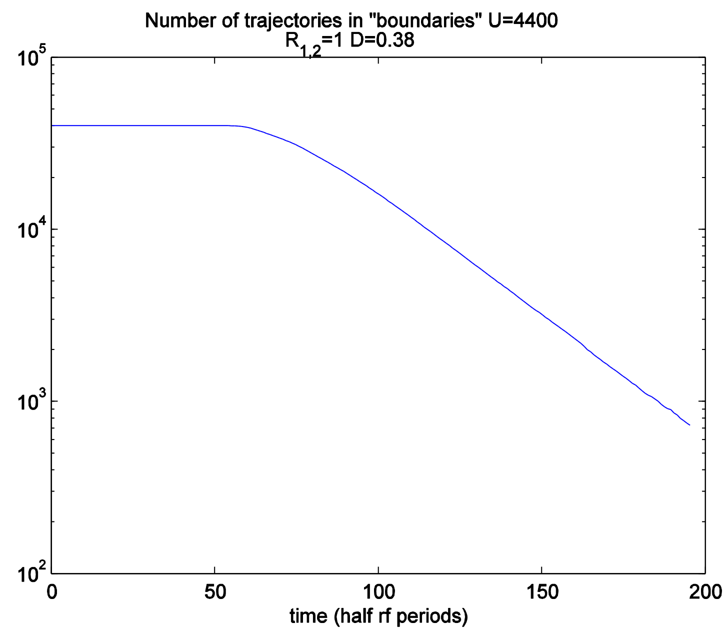
Simulations



Simulations

- **Typical output of simulation software**



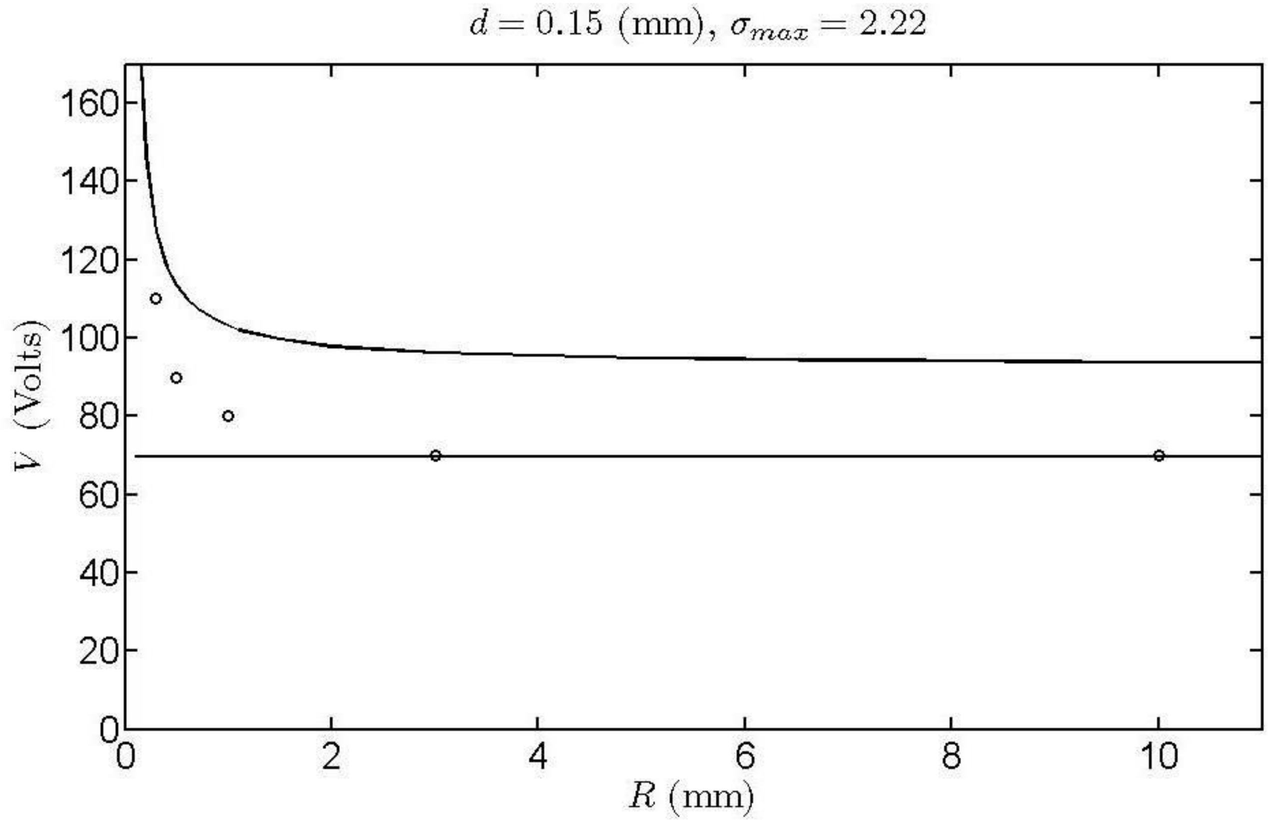


- **Left: Number of electrons**
- **Right: Number of electron bunches**

Comparisons between simulations and theory

- **Two gap widths were simulated, d=0.15 mm, and d=3.8 mm. SEY_max=2.22, W_1=30 eV, and W_e=3 eV**
- **For small gap width we should expect the approximate theory to give a too high threshold, since we essentially have parallel plates, and the main contribution to the avalanche will come from the electrons with** $v_i \approx 2v_\omega$
- **Whereas the approximation gives** $v_i \approx \frac{3}{2} v_\omega$

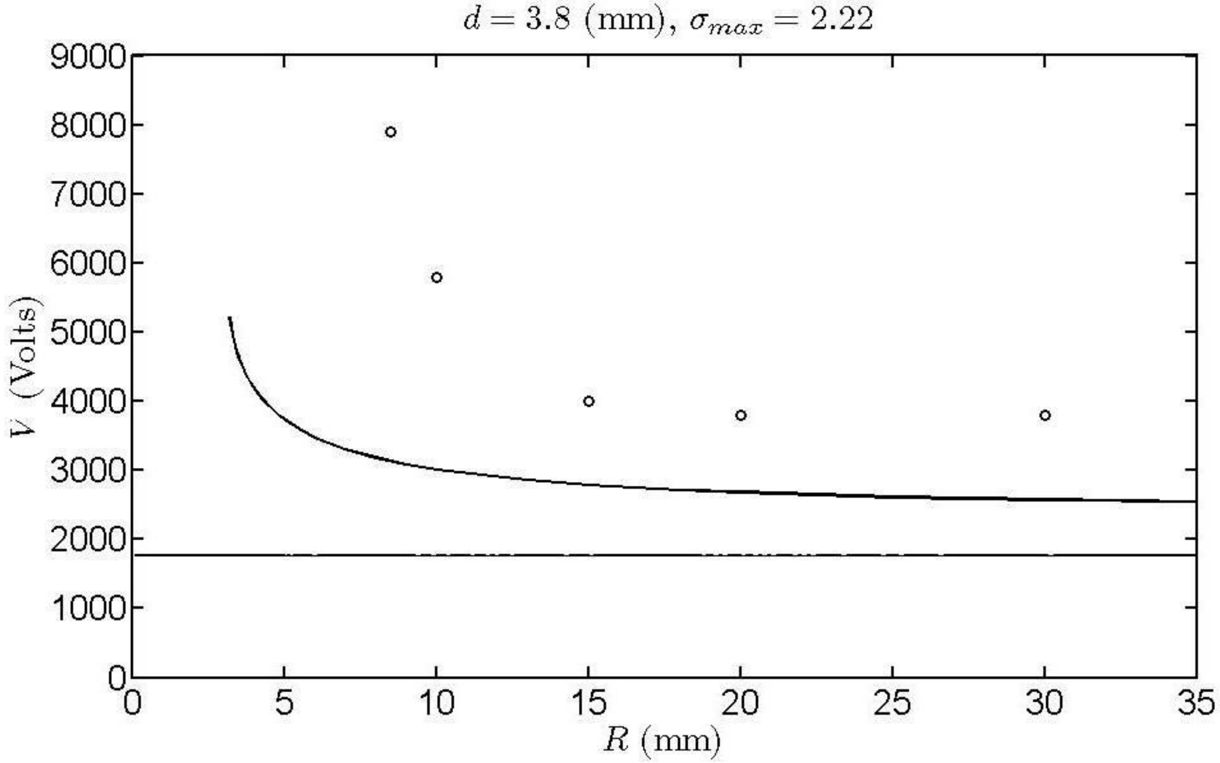
Comparisons between simulations and theory



Small gap

Comparisons between simulations and theory

- **For the big gap, resonance is suppressed, and the approximate theory should give better agreement, compared to the resonant theory**



Conclusions

- Qualitative agreement between approximate theory and simulations
- The electron dilution mechanism brought on by the curved geometry is very important. The resonant theory is not able to incorporate this
- There is a smallest radius for every material, under which, no two-sided multipactor should be possible
- Two-sided multipactor in any realistic Helix system (big gap, small radius) should not be possible!