Electrostatic discharges on spacecrafts solar panels: coupled model of a cathode spot and flash-over propagation in vacuum

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## Context

<table>
<thead>
<tr>
<th>ESD</th>
<th>Plasma bubble</th>
<th>BO &amp; FO</th>
<th>Secondary arc</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Cover glass" /> <img src="image" alt="Conductor" /></td>
<td><img src="image" alt="Plasma bubble" /></td>
<td><img src="image" alt="BO &amp; FO" /></td>
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- A cathodic spot is created
- The plasma bubble expands over the SP
- Two currents are carried by the plasma
- Cause permanent damage

- Because of interactions with space environment Electrostatic Discharges (ESD) appear on spacecrafts solar panels (SP)
- It leads to a plasma bubble that expands over the SP
- The plasma carries two currents: the blow-off (BO) that empty the conductor capacitance and the flash-over (FO) that is recollected over the SP
- The plasma bubble is a conductive environment that may lead to secondary arcs
Context

Our objective is to study the evolution of the FO over the SP from the plasma creation at the cathode spot to the extinction.
ESD → Plasma bubble → BO & FO → Secondary arc

Context

- System in ultra-high vacuum (mass and charge conservation)
- Diffuse anode
- Axial geometry: particles emitted in every directions and spherical plasma
- Cathode material: silver, aluminium or silicon (+ copper)
Model presentation
Microscopic scale

Macroscopic scale
Current conservation

Energetic balance in the pre-sheath

Energetic balance at the surface

Poisson’s law

Langmuir current
Current conservation

\[ J = J_{cat} + J_{sec} + J_i - J_{bk} = J_{ep} - J_{ip} \]

- \( J_{cat} \) = Emitted electrons
- \( J_{sec} \) = Secondary electrons
- \( J_i \) = Incoming ions
- \( J_{bk} \) = Electrons coming back from the plasma
- \( J_{ep} \) = Current density at the spot surface
- \( J_{ip} \) = Current density in the plasma

\[ J_{cat} = (A_T T^2 + A_F E^x) \exp \left( - \left( \frac{T^2}{B_T} + \frac{E^2}{B_F} \right)^{1/2} \right) \] Murphy & Good thermo-field equation
Energetic balance at the surface

\[ S_i + S_{bk} + S_{jle} = S_n + S_{cat} + S_{sec} + S_{cd} \]

- Given by ions
- Given by electrons from plasma
- Given by Joule effect
- Conduction distance computed with Fourier law around the spot
- Lost by the neutrals emission
- Lost by the electrons emission
- Lost by the secondary electrons emission
- Lost by conduction

\[ T_s = 300K \]
**Energetic balance in the pre-sheath**

<table>
<thead>
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<th>Neutral emission flux</th>
<th>Mass conservation</th>
</tr>
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<td>• Surface near cathodic spot also emit neutrals over a distance $l$</td>
<td>• All neutrals are ionized</td>
</tr>
<tr>
<td>• We integrate the distribution function over a disk of radius $l$ considering a view angle</td>
<td>• Mass must be conserved</td>
</tr>
</tbody>
</table>

\[
\Phi'_n = \Phi_n \left( 1 + \frac{1}{2\pi} \ln \left( \frac{l^2 + a^2}{2a^2} \right) \right)
\]

\[
\Phi_i = \Phi'_n
\]
Energetic balance in the pre-sheath

\[ S_{joule} + S_{e, in} + S_{n, in} = S_{i, out} + S_{e, out} \]

Given by ionizing electrons

Given by Joule effect

Given by incoming neutrals

Lost with ions

Lost with electrons

\( Z \) is calculated with the Saha equation (2-3 for silver)
Poisson’s law in the sheath

\[ \nabla \varphi = - \frac{dE}{dx} = - \frac{e}{\varepsilon_0} (Ze_n - n_e) \]

\[ eZe_n(x) = \frac{J_i}{v_i(x)} \]

\[ en_e(x) = e \left( n_{cat}(x) + n_{sec}(x) + n_{ep}(x) \right) = \frac{(J_{cat} + J_{sec})}{v_e(x)} + en_{ep}(x) \]

\[ \varphi(0) = 0 \quad E(0) = E_s \]

\[ \varphi(x_g) = \varphi_g \quad E(x_g) = E_g \]
Child-Langmuir law

\[ I = 2\pi a^2 j \]

\[ I = \int \int J_{CL} \]

Spot characteristic time << expansion time step → Instantaneous current conservation
Energetic balance in the pre-sheath

\[ T_e \]

Energetic balance at the surface

\[ T_S \]

Current conservation

\[ I \]

Poisson’s law

\[ E_s \]

Langmuir current

\[ \varphi_B \]
Results
Plasma potential

![Graph showing plasma potential vs total current for Silver and Copper. The graph highlights the Thermo-field and Thermo-ionic regions.]
Electric field $\approx 10^9$ V/m
Plasma potential

![Graph showing the relationship between plasma potential and total current for silver and copper](image)

- **Plasma potential (V)**
- **Total current I (A)**

Legend:
- Blue line: Silver
- Orange line: Copper

**$\varphi_{min}$**
Plasma potential

\[
\frac{d\varphi}{dl} > 0
\]
Surface temperature

![Graph showing surface temperature versus total current for Silver and Copper.](image)
Electrons temperature

![Graph showing the relationship between electrons temperature (Te) in eV and total current (I) in A for Silver and Copper. The graph indicates that as the total current increases, the electrons temperature decreases for both materials.](image)
Plasma density

Electrons density (part/m³) vs Total current I (A)

- Silver
- Copper
Presentation of EMAGS3 results
Flash-over propagation and extinction

Simulation stops when \( \Phi_{Bubble} < \Phi_{min} \)
Conclusion

• We have a Flash-over propagation model with creation and extinction of plasma
• Coupled model between cathode spot emission and current collection over solar panel
• Limiting conditions by the spot = limiting condition for the expansion
• Good agreement with experimental data
Perspectives

• Evolution over large solar panels
  – Current limited by the solar panel size
  – Thermal effect on large scales
  – Density evolution in space

• Solar panel electric circuit
  – Dynamic effects
  – Secondary arcing
Thank you!