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TAMING ELECTRON AVALANCHES: MULTIPACTION-RESISTANT CABLE DESIGN FOR HIGH-POWER SIGNALS IN SPACE

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Abstract

Trusted signal transmission is fundamental to mission-critical communication systems operating in space. Whether supporting spaceflight telemetry, tracking, and command (TT&C), satellite communications, radar, or scientific instrumentation, these systems must function reliably under the extreme conditions of deep-space vacuum. In this environment, electronics are exposed to phenomena not seen by terrestrial systems. Chief among these is multipaction, an electron avalanche event capable of degrading signal integrity and catastrophically damaging components.

This paper examines the critical role of multipaction-resistant coaxial cable assemblies in enabling high-power signal transmission in space, particularly as next-generation RF and microwave systems move toward higher power levels, increased frequencies, and continued miniaturization. Grounded in the physics of multipaction and informed by industry experience, the discussion explores key design factors such as connector geometry, material selection, surface coatings, and thermal management that influence multipaction resilience. The paper concludes by advocating a system-level design approach that accounts for interactions across the entire RF chain. In particular, it emphasizes the critical role of computer-aided simulations in mitigating application-specific multipaction challenges in high-power coaxial cables for deep-space missions.

Threats to Signal Transmission in the Vacuum of Space

Unlike ground-based systems, where atmospheric pressure (≈760 Torr) suppresses free-electron acceleration and enables convective cooling, space-based systems operate in a high-vacuum environment typically ranging from approximately 10^{-7} Torr in low-Earth orbit to below 10^{-10} Torr in geostationary orbit, conditions that allow electrons to travel long distances without collisions.

Historical experience highlights the significance of these risks. During the 1990s, multipaction-related effects were observed in high-power satellite payload RF hardware, particularly within transmission components such as coaxial feeds, waveguides, and connectors. As operating frequencies and power levels increased, similar issues emerged in early Ka-band payloads during the 2000s. These events underscore the complexity of achieving multipaction resistance in space communication hardware and demonstrate that robust cable and connector design is mission-critical for reliable high-power signal transmission in deep-space environments.

Multipaction: When Electrons Go Rogue

Multipaction is a resonant electron discharge phenomenon that occurs in high-vacuum environments. It most commonly arises in high-power, high-frequency RF and microwave transmission systems operating in space, including amplifiers, antennas, coaxial cables, and connectors. This process begins when free electrons, aligned with the phase of an RF field, are accelerated across a gap. If these electrons gain sufficient kinetic energy and strike conductive surfaces, secondary electron emissions can occur, leading to a self-sustaining cascade known as an electron avalanche.

In space-based communication systems, multipaction represents a critical reliability risk. Long mission durations and the inability to perform in-situ repair mean that multipaction events can have significant mission-level consequences. Once initiated, multipaction can severely degrade system performance or lead to permanent hardware damage through localized heating, material erosion, and electrical breakdown. The consequences of multipaction on signal transmission include:

- **Signal loss/Attenuation** – Electron clouds generated by multipaction absorb power from the RF signal, reducing signal strength.
- **Signal Distortion** – Non-linear interactions between the RF field and the electron population can alter the signal waveform, producing unwanted frequency components such as harmonics and intermodulation.
- **Increased Noise** – Fluctuating electron currents introduce broadband noise that can increase bit error rates (BER) and the likelihood of data corruption in digital communication systems.
- **Thermal Runaway and Arcing** – Concentrated electron impacts cause localized heating that can erode protective surface coatings, degrade dielectric materials, and, in severe cases, melt conductors or trigger arcing.

The Perfect Storm: How Multipaction Begins

Multipaction can be highly destructive, but it occurs only when three conditions are simultaneously satisfied.

1. **Mean Free Path (MFP) Dominance** – In high-vacuum environments, the average distance an electron travels before colliding with another particle (the mean free path) is extremely large. Without particle collisions, free electrons can be efficiently accelerated by high-power, high-frequency RF electric fields, gaining sufficient kinetic energy to produce secondary electron emissions. MFP dominance occurs when the electron mean free path exceeds the gap dimensions between surfaces within connectors and cable interfaces.
2. **RF Electric Field Resonance** – Resonance occurs when the electron's transit time across a gap synchronizes with the phase of the oscillating RF electric field. Under these conditions, electrons strike the opposing surface at or near peak acceleration. These phase-aligned impacts promote the development of a self-sustaining electron cascade and are commonly classified as:

   - **First-Order Multipaction** – Electrons traverse the gap in half an RF cycle. This mode is the most hazardous due to its low threshold voltage.
   - **Second-Order Multipaction** – Electrons traverse the gap over a full RF cycle.
   - **Higher-Order Multipaction** – These require higher RF voltages and are therefore less common.

3. **Secondary Electron Yield Greater Than One (SEY > 1)** – Multipaction becomes self-sustaining only if SEY exceeds unity. In this regime, each incident electron generates more than one secondary electron on average, causing the electron population to grow exponentially, leading to an electron avalanche. SEY is strongly influenced by the surface material and condition, as well as by the incident electron's kinetic energy and angle of impact.

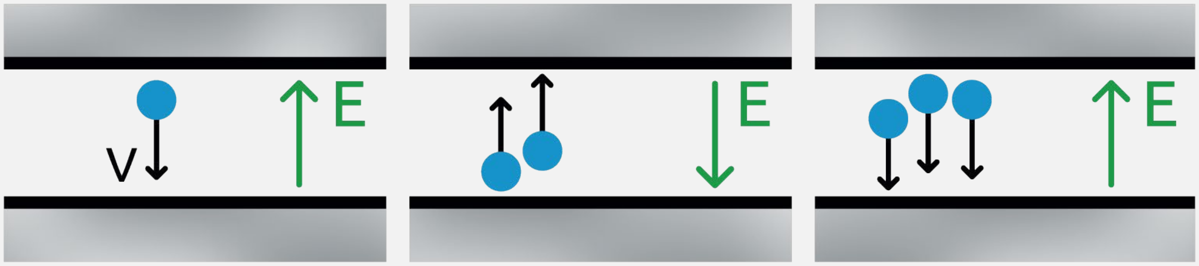


Illustration of Secondary Electron Emissions

Outsmarting Multipaction with Connector Geometry

Multipaction rarely develops within the uniform sections of coaxial cables, where conductor spacing is tightly controlled and dielectric coverage is continuous. Instead, it most often originates in connector-to-cable transition regions, and connector-to-connector interfaces, where manufacturing and assembly tolerances can introduce unplanned air gaps. Within these regions, the combined effects of gaps, operating frequency, and local electric-field distributions can align to support resonant electron trajectories.

Key features that improve multipaction resistance include:

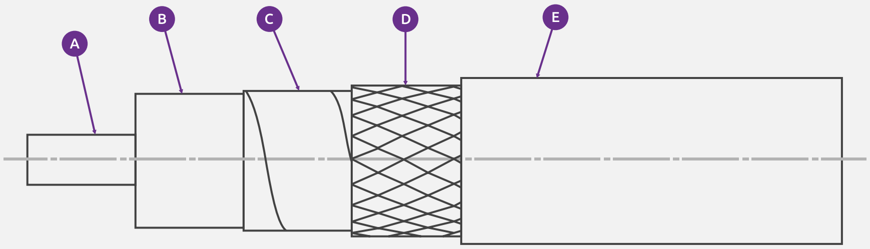
- **Rounded Edges** – Smooth transitions reduce localized electric-field enhancement and inhibit electron accumulation, providing greater resistance to multipaction than sharp corners.
- **Slanted/Wedge-Shaped Surfaces** – Angled surfaces at connector interfaces eliminate parallel gaps, disrupting the MFP dominance condition required for electron avalanche formation.
- **Strategically Placed Venting Holes** – Even low-outgassing materials release volatiles in high-vacuum environments. Proper venting reduces the risk for pressure-induced mechanical stress of critical surfaces.

How Smart Material Choices Keep Electrons in Check

Material choices and surface treatments affect the electrical, thermal, and surface characteristics that influence a coaxial cable's resistance to multipaction.

Typical Coaxial Cable Assembly

Ⓐ Center conductor
Ⓑ Dielectric
Ⓒ Inner shield
Ⓓ Outer braid
Ⓔ Jacket



Key material considerations include:

- **Advanced Dielectrics** – Concentrated electron impacts cause localized heating, leading to coating erosion, dielectric degradation, outgassing, and, in severe cases, conductor melting or arcing. Thermally conductive dielectrics, such as Fluoroloy®, are well suited for high-power space applications, providing electrical insulation while efficiently dissipating heat from critical regions to mitigate damage.

  Lower-cost alternatives, such as PTFE, offer effective electrical insulation and help minimize gaps within cable assemblies, though they lack thermal conductivity. Fluoroloy represents a deliberate performance trade-off, offering effective thermal management but at higher cost and with moisture sensitivity, requiring controlled packaging and selective use where performance demands justify its inclusion.

- **Connectors** – Beryllium copper is well-suited for space-grade connectors due to its high strength-to-weight ratio, excellent electrical and thermal conductivity, and strong resistance to fatigue, shock, vibration, and corrosion. These properties support stable electrical performance in harsh environments and across wide temperature extremes.

  Alternative connector materials, including stainless steel, brass, aluminum, and bronze, offer trade-offs in mechanical strength, thermal conductivity, and multipaction resistance.

- **Low-Emission Coatings and Surface Treatments** – Coating the inside of connectors with materials that have inherently low SEY can significantly reduce multipaction risk. Emerging surface treatments, including laser-ablation techniques that nanostructure surfaces, also suppress SEY by trapping secondary electrons.

System-Level Analysis and Predictive Modeling

Ultimately, multipaction arises from interactions across the entire RF chain. Power level, operating frequency, thermal environment, size constraints, and impedance matching collectively define risk, making a system-level design approach essential — especially as RF and microwave systems advance toward higher power, higher frequencies, and continued miniaturization.

These competing constraints make predictive computer-aided simulation essential for evaluating design options and guiding decisions before hardware is built. Advanced 3D electromagnetic simulation tools, such as CST Studio Suite, enable detailed analysis and optimization of RF components and systems. Its Spark3D add-on further supports assessment of multipaction and corona risk by tracking electron trajectories and identifying low-order resonant modes.

The Harsh Realities of Space: Cables Don't Get a Second Chance

In the high-vacuum environment of space, multipaction develops quietly, accelerates rapidly, and can end a mission without warning. With no atmosphere to slow free electrons, no technician to reseat a connector, and no opportunity for repair once launched, multipaction represents a failure mode for which post-launch correction is simply not possible.

When missions depend on uninterrupted high-power, high-frequency signal transmission across millions of miles, success hinges on respect for the physics at play and the rigor of intelligent design. Achieving reliable coaxial cable assemblies for space applications requires deep expertise in electron dynamics, materials science, geometric influences, tight-tolerance manufacturing, and simulation-driven validation from the outset. MegaPhase exemplifies this philosophy — treating cables and connectors not as commodities, but as engineered systems purpose-built for spaceflight.

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About us

Founded in 1998 and headquartered in Stroudsburg, Pennsylvania, MegaPhase designs and manufactures high-performance RF coaxial cables and connectors for OEMs in critical markets including test instrumentation, defense, aerospace, telecommunications, and satellite systems. Serving more than 500 customers in 30 countries—including major technology leaders and the U.S. government—MegaPhase is best known for its industry-leading GrooveTube® technology, a breakthrough flexible cable design used in high-reliability, high-power, and phase-defined applications across ground, sea, air, and space platforms. All products are manufactured in-house, tested 100% in a state-of-the-art RF lab up to 110 GHz, and engineered to deliver exceptional phase stability, low loss, and long-term measurement repeatability, helping customers achieve more reliable results at a lower cost per measurement.

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