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# Deep Charging Evaluation of Satellite Power and Communication System Components

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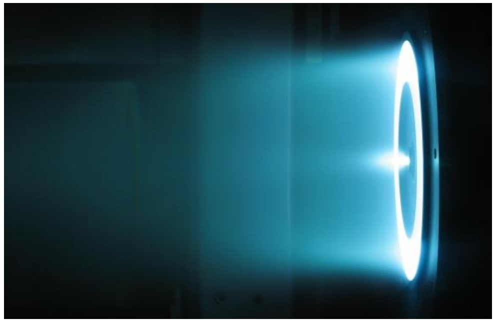
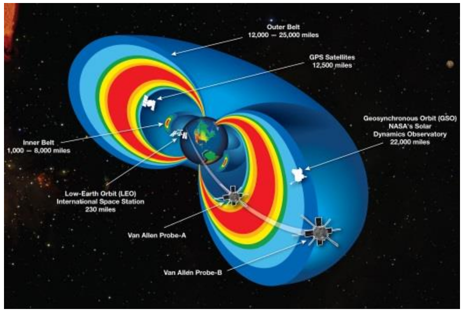
# Motivation

- SSL has been using Electric Propulsion thrusters for many years to provide station-keeping of their communication satellites in Geosynchronous Earth Orbit (GEO)
- A logical extension of SSL's electric propulsion program was to provide Electric Orbit Raising (EOR) services
  - EOR missions benefit from reduced launch mass and increased on-orbit payload (compared to traditional chemical propulsion technologies)
- A trade-off associated with EOR is the unavoidable transits through Earth's radiation belts
- Exposure of satellite systems to high energy charged particle environments in the radiation belts provides an opportunity to experience deep charging scenarios



Credit: JPL

Credit: SSL



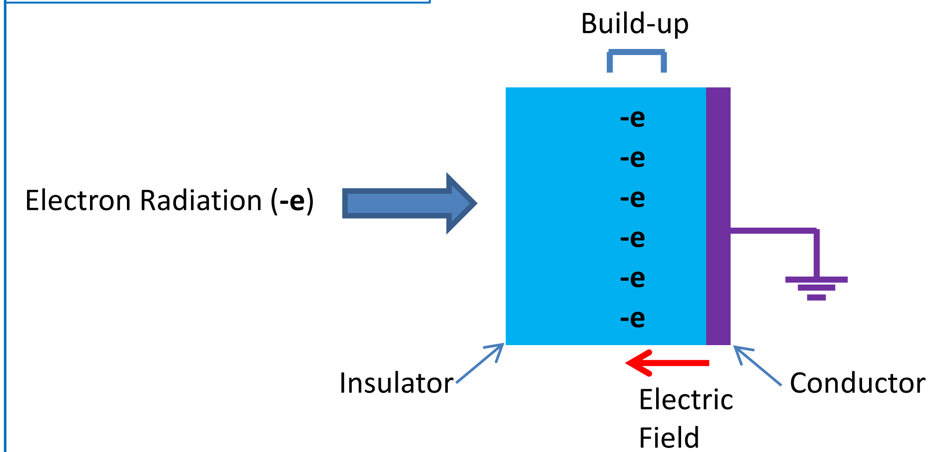

Credit: NASA RBSP

# Deep Charging

- For the work described here, "Deep Charging" or "Internal Charging" refers to charge penetration deep into an insulating material (dielectric)
  - As Garrett notes, internal charging can also occur on/in an electrically floating conductor [1]
- Typically testing focuses on electron penetration into the material, since the range of electrons is much greater than ions with the same energy
- Primary interest in deep charging is focused on scenarios in which the charged insulator is in close proximity to a conductor (particularly a grounded conductor)
- **The threat associated with deep charging is the formation of an electrostatic discharge (ESD) or electrical arc**

*When the electric field strength exceeds the dielectric strength of the material an Electrostatic Discharge (ESD) can occur*

***Deep Charging Scenario***

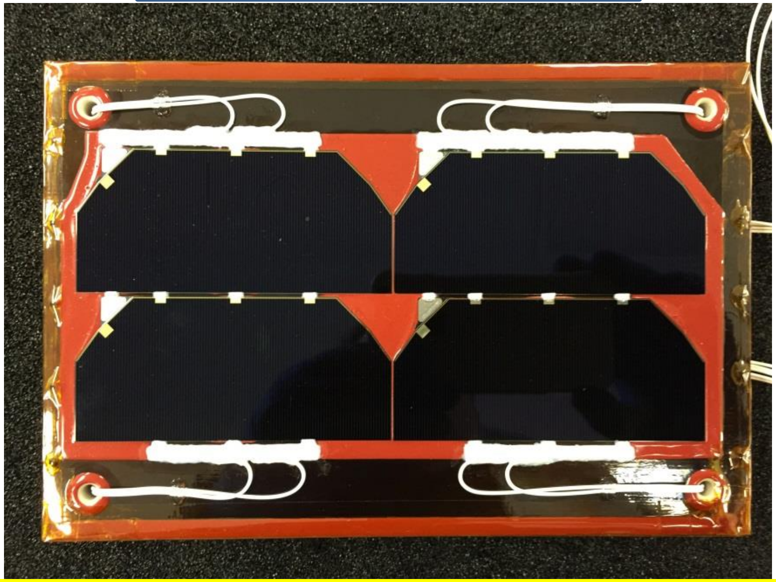



*Electrostatic Discharge (ESD) events or "arcs" can damage insulators, disrupt digital signals, and even destroy sensitive electronics*

# Deep Charging Test/Evaluation

- The potential deep charging risk associated with EOR missions warranted testing of critical systems on SSL spacecraft including power and communication systems (since they were directly exposed to the environment)
- SSL partnered with NASA's Marshall Space Flight Center to perform deep charging tests of flight-like coupons scaled to fit in the vacuum test chambers

**Solar Array Power System**



**Cell Interconnect Coverglass (CIC) Coupon (Photovoltaic Cells Arranged in 2 Strings)**

**Microwave Communications**

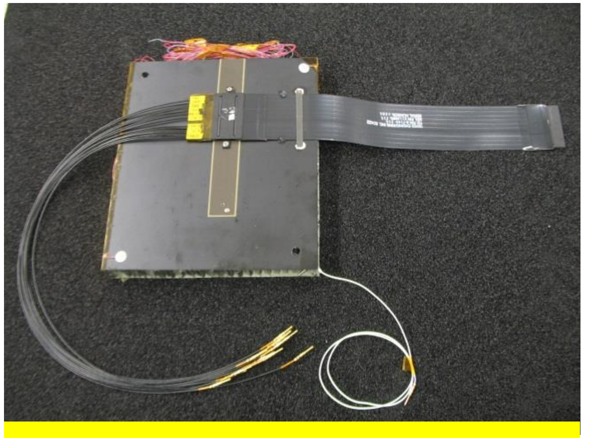
**Semi-Rigid Coaxial Cable (SMA Connections)**

# Wire Coupons

- Wire coupons are scaled versions of solar array wiring systems
- Solar array wiring can carry multi-amp currents
- Wiring systems are on both the front (sun facing) and back side of the solar arrays

**Back Side Round Wire**

**Front Side Round Wire**



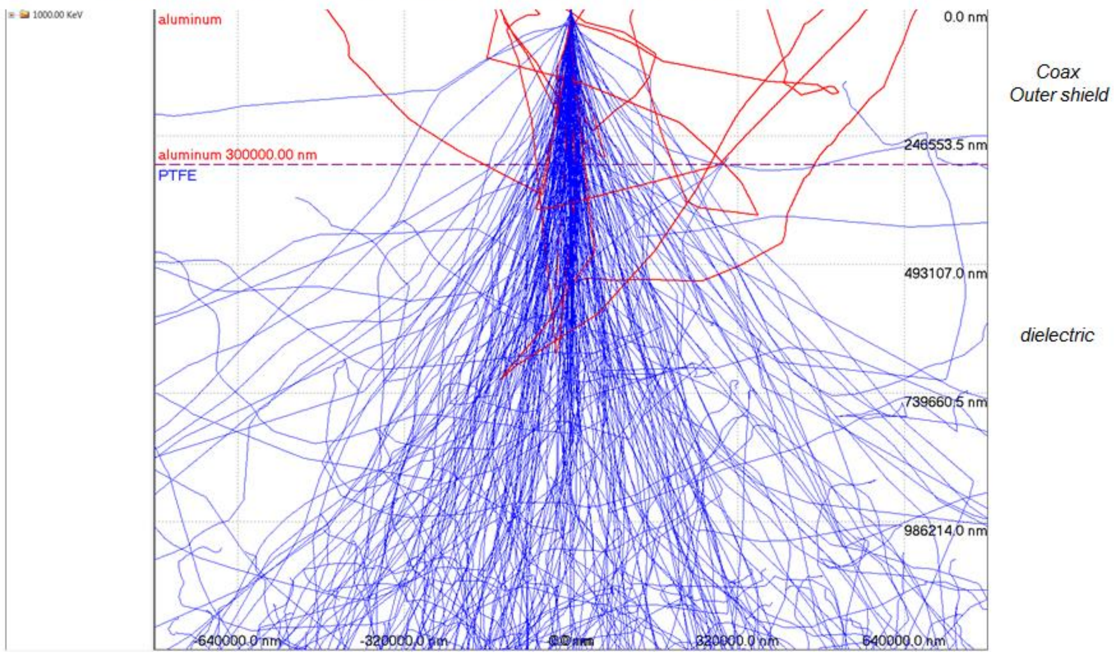
**Ribbon Harness**

# Establishing Test Energies

- Electron penetration into a material can be modeled
- SSL modeled electron penetration into materials and assemblies associated with the Wire and CIC coupons as well as the Coaxial Cable
- The electron energies used in the test were chosen based on simulations of electron range in all of the relevant dielectrics on the samples
- **Two energies were selected for the test: 1 MeV and 300 keV**

**Appendix 2 – Coax Simulation**

◆ **Coax simulation with 1MeV energy (about 12 mils outer shield and 40mils PTFE)**




SSL model of electron penetration in a coaxial cable.

The model predicts the majority of electrons penetrate deep into the Teflon (PTFE) Insulator (aka “dielectric”)

# Flux and Fluence Levels

- SSL analyzed the EOR mission profiles and established expected electron flux and fluence levels
  - Detailed description of this process is provided by Wong in a separate paper at this conference [2]

**Electron Exposure Test Levels for CIC Coupon and Coaxial Cable Sample**

| Coupon Description | Fluence at 300 keV (e-/cm$^2$) | Fluence at 1 MeV (e-/cm$^2$) | Electron Flux (nA/cm$^2$) | Exposure Time at 300 keV (hrs) | Exposure Time at 1 MeV (hrs) |
|---|---|---|---|---|---|
| CIC Coupon | 3.56E12 | 8.4E11 | 0.03 | 5.3 | 1.25 |
| Coaxial Cable | 3.56E12 | 8.4E11 | 0.03 | 5.3 | 1.25 |

**Electron Exposure Test Levels for Wire Coupons**

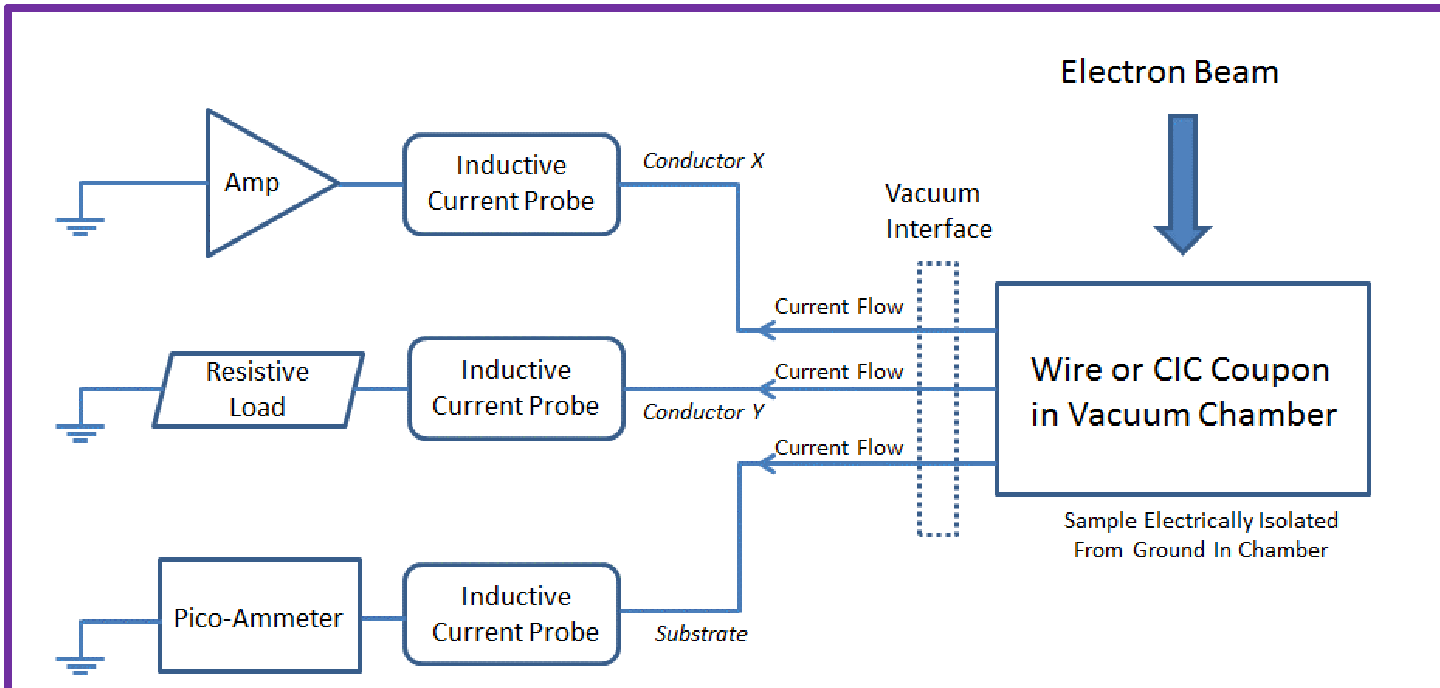
| Coupon Description | Fluence at 300 keV (e-/cm$^2$) | Fluence at 1 MeV (e-/cm$^2$) | Electron Flux (nA/cm$^2$) | Exposure Time at 300 keV (hrs) |
|---|---|---|---|---|
| Wire Coupon (front side) | 3.56E12 | N/A | 0.03 | 5.3 |
| Wire Coupon (back side) | 3.56E12 | N/A | 0.03 | 5.3 |
| Ribbon Coupon | 3.56E12 | N/A | 0.03 | 5.3 |

# Deep Charging and Electrostatic Discharge (ESD) Detection

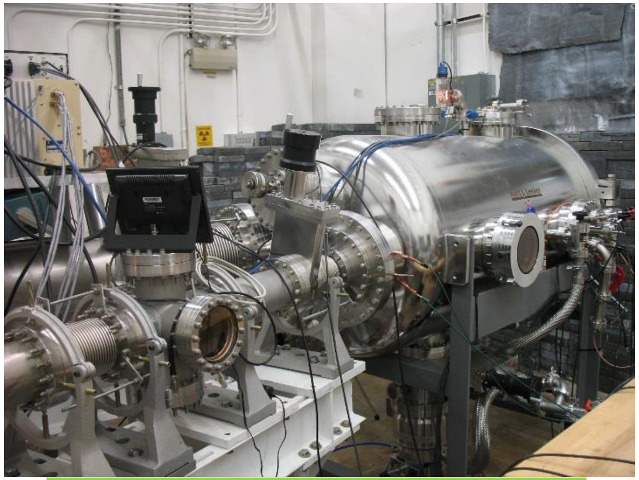
- Deep charging ESD occur as a result of dielectric breakdown in a charged insulator
- Typically, breakdown of an insulator is accompanied by a flow of electrons out of the insulator into a nearby conductor (at a lower potential)
- The flow of electrons into a conductor is measured as current flow

Inductive Current Probes were the key diagnostic for detecting ESD

Substrate steady state current levels monitored to verify electron beam application

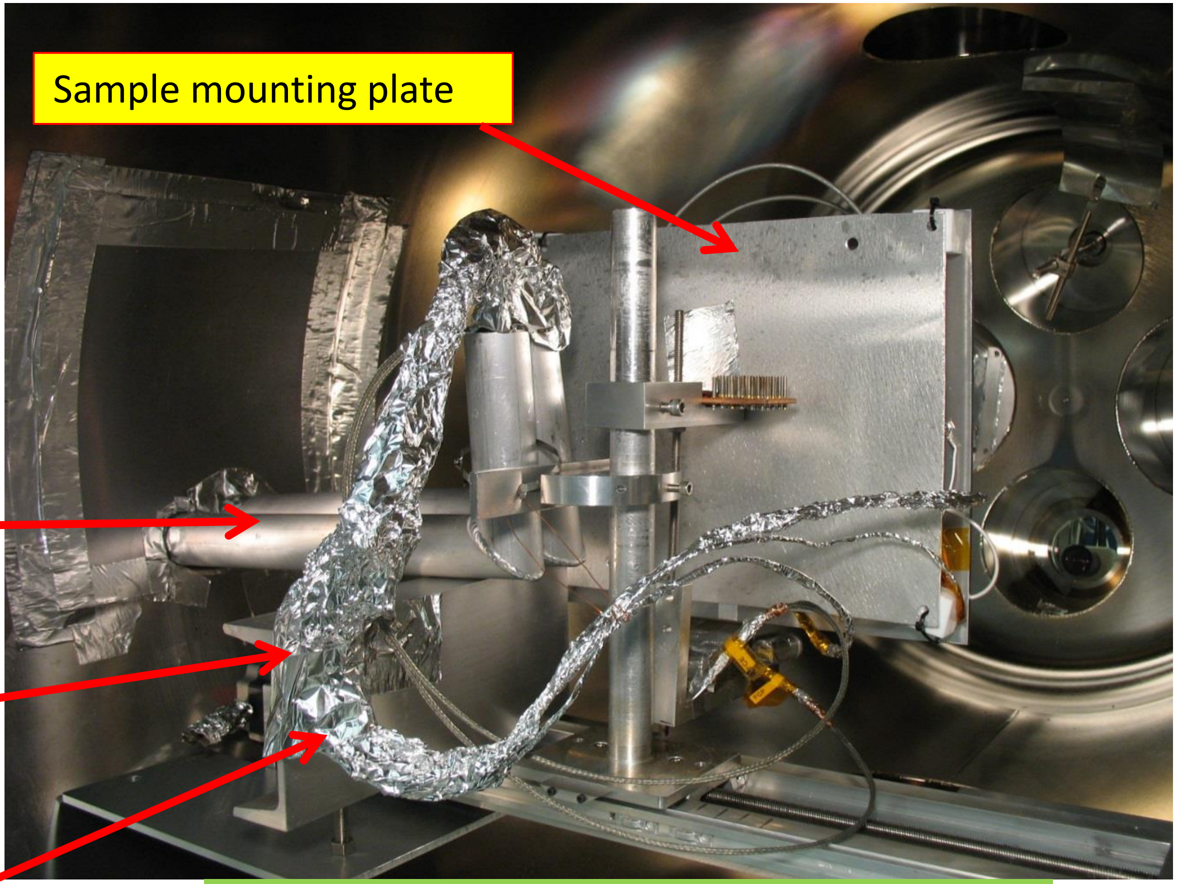


# Test Setup: The Quest to be "ESD Clean"



Electron Beam Line and Sample Chamber

**Must minimize ESD due to surface charging and ESD on feed-through wiring**




Inside the Sample Chamber – Behind the Sample Mounting Plate

Thick-walled tubes stop the primary electrons from charging the feed-through wiring

Wire connections are "hidden" behind the sample mounting plate which acts as shielding

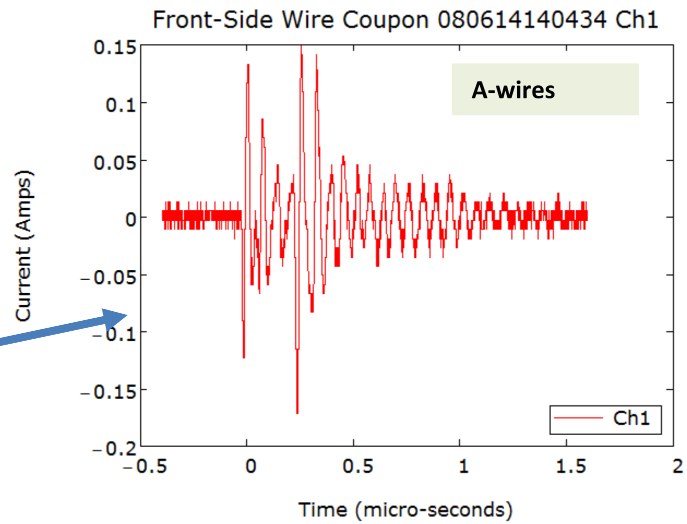
Foil applied to connection wires to minimize surface charging due to scattered electrons

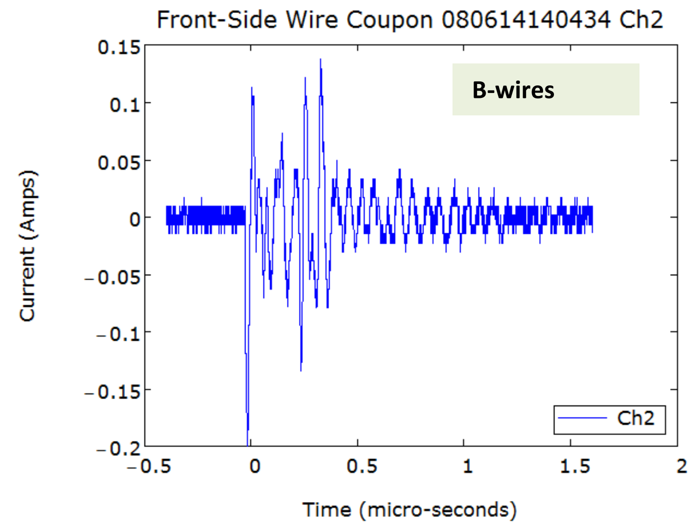
# Anatomy of an ESD Event

*Front-side Round Wire Coupon*

**Small peak magnitude**

**Almost identical to B-wires. Suggests induced current waveforms**



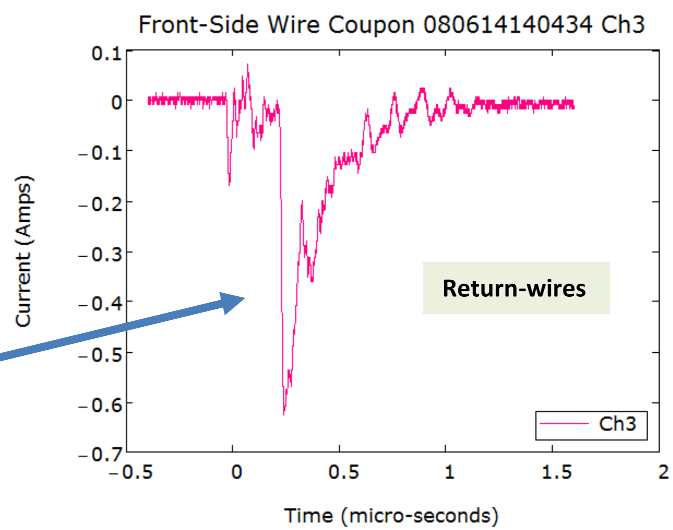



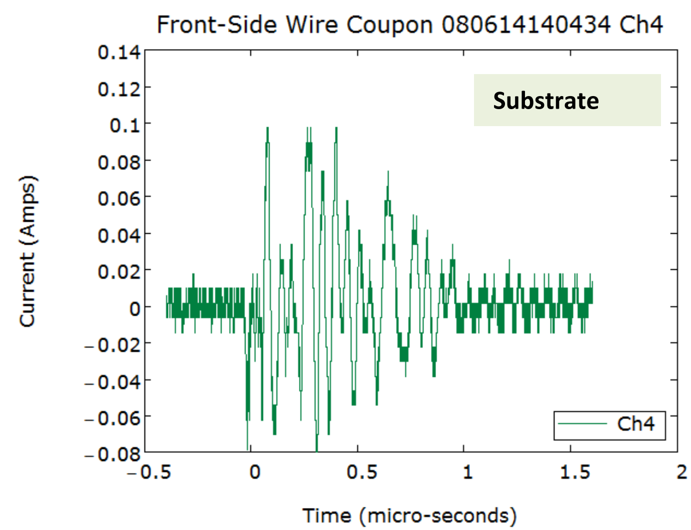

**Unique signature**

**Negative-going pulse**

**Higher peak magnitude than other signals**

**Pulse width larger than other channels**



# Results Summary: Passive Circuit Tests

The objective of the passive circuit tests was to determine if any deep charging ESD events occurred, and establish overall magnitude levels

| Passive Circuit Testing | | | | | |
|---|---|---|---|---|---|
| **Sample** | **Electron Energy (MeV)** | **Exposure Time (Hours)** | **No. of Scope Triggers** | **No. of Deep Charging ESD Events** | **Largest Peak ESD Current Detected** |
| Front Side Wire | 0.3 | 5.3 | 65 | 8 | 700 mA |
| Back Side Wire | 0.3 | 5.3 | 26 | 1 | 500 mA |
| Ribbon Harness | 0.3 | 5.3 | 5 | 2 | 120 mA |
| Coaxial Cable (w/bleed resistors) 1.6X Flux | 0.3 | 1.0 | 0 | 0 | 0 A |
| Coaxial Cable (w/bleed resistors) 1X Flux | 1.0 | 1.3 | 0 | 0 | 0 A |
| Bare Aluminum (Control) 1X Flux | 0.3 | 2.0 | 7 | 0 | <200 mA |
| Bare Aluminum (Control) 3X Flux | 0.3 | 0.5 | 6 | 0 | <200 mA |
| Bare Aluminum (Control) 1X Flux | 1.0 | 1.0 | 1 | 0 | <200 mA |
| Bare Aluminum (Control) 8X Flux | 1.0 | 0.5 | 0 | 0 | 0 A |

**Control tests conducted to help differentiate spurious signals from deep charging ESD's**

**All inductive current probes were connected to a fast oscilloscope ("scope") channel. A majority of the scope triggers did not meet the criteria associated with a deep charging ESD waveform (see chart titled "Anatomy of an ESD Event")**

# Results Summary: Active Circuit (Powered) Tests

The objective of the active tests was to determine if a deep charging ESD event would lead to a sustained arc. Each sample was connected to a Solar Array Simulator (SAS) power supply set to typical satellite power levels.

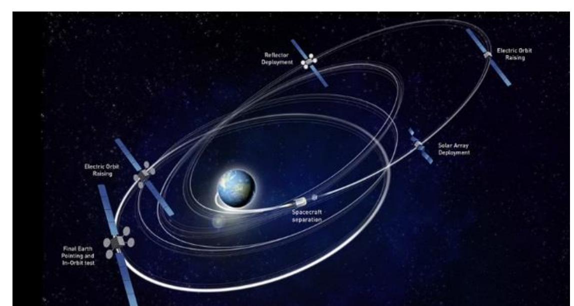
| **Active Circuit Testing** | | | | | | |
|---|---|---|---|---|---|---|
| **Sample** | **Electron Energy (MeV)** | **Exposure Time (Hours)** | **SAS Voltage (Volts)** | **SAS Current (Amps)** | **No. of Scope Triggers** | **No. of Sustained Arc Events** |
| CIC (Solar Cells) [1400 Volt Bias] | 0.3 | 5.3 | 108 | 0.55 | 1 | 0 |
| CIC (Solar Cells) [1400 Volt Bias] | 1.0 | 1.25 | 108 | 0.55 | 0 | 0 |
| CIC (Solar Cells) [0 Volt Bias] | 0.3 | 5.3 | 108 | 0.55 | 59 | 0 |
| CIC (Solar Cells) [0 Volt Bias] | 1.0 | 1.25 | 108 | 0.55 | 9 | 0 |
| Front Side Wire | 0.3 | 5.3 | 108 | 4.0 | 11 | 0 |
| Back Side Wire | 0.3 | 5.3 | 108 | 4.0 | 3 | 0 |
| Ribbon Harness | 0.3 | 5.3 | 108 | 4.0 | 0 | 0 |

**No sustained arcs were found.**

# Conclusion

- A deep charging test campaign devised by Space Systems Loral (SSL) has been carried out at NASA's Marshall Space Flight Center (MSFC)
- The test campaign focused on engineering evaluations of flight-like samples
  - Solar array wire coupons (3 types of wiring systems)
  - A photovoltaic cell coupon (known as a "CIC" coupon)
  - A semi-rigid coaxial cable (used for microwave communication systems)
- Two types of tests were conducted: Passive Circuit and Active Circuit
  - Active circuit tests involved applying power to the sample under investigation. Power levels were commensurate with typical SSL satellite operating conditions
- Based on detection of current pulses generated during passive circuit testing, there is evidence that some Electrostatic Discharge (ESD) events did occur as a result of deep charging
- **All samples showed no signs of damaging or sustaining arcs due to deep charging**

Credit: Space News




Credit: Space News

# References

[1] H. B. Garrett and A.C. Whittlesey, "Spacecraft Charging, An Update", *IEEE Transactions On Plasma Science*, VOL. 28, NO. 6, December 2000

[2] Kit Frankie Wong and Wousik Kim, Deep Charging Requirement and Analysis Approach for EOR to GEO, Paper No. 0030, Proceedings of the 14th Spacecraft Charging Technology Conference, ESA/ESTEC, Noordwijk, NL, 04-08 April 2016

Deep Charging Test

# BACKUP INFORMATION

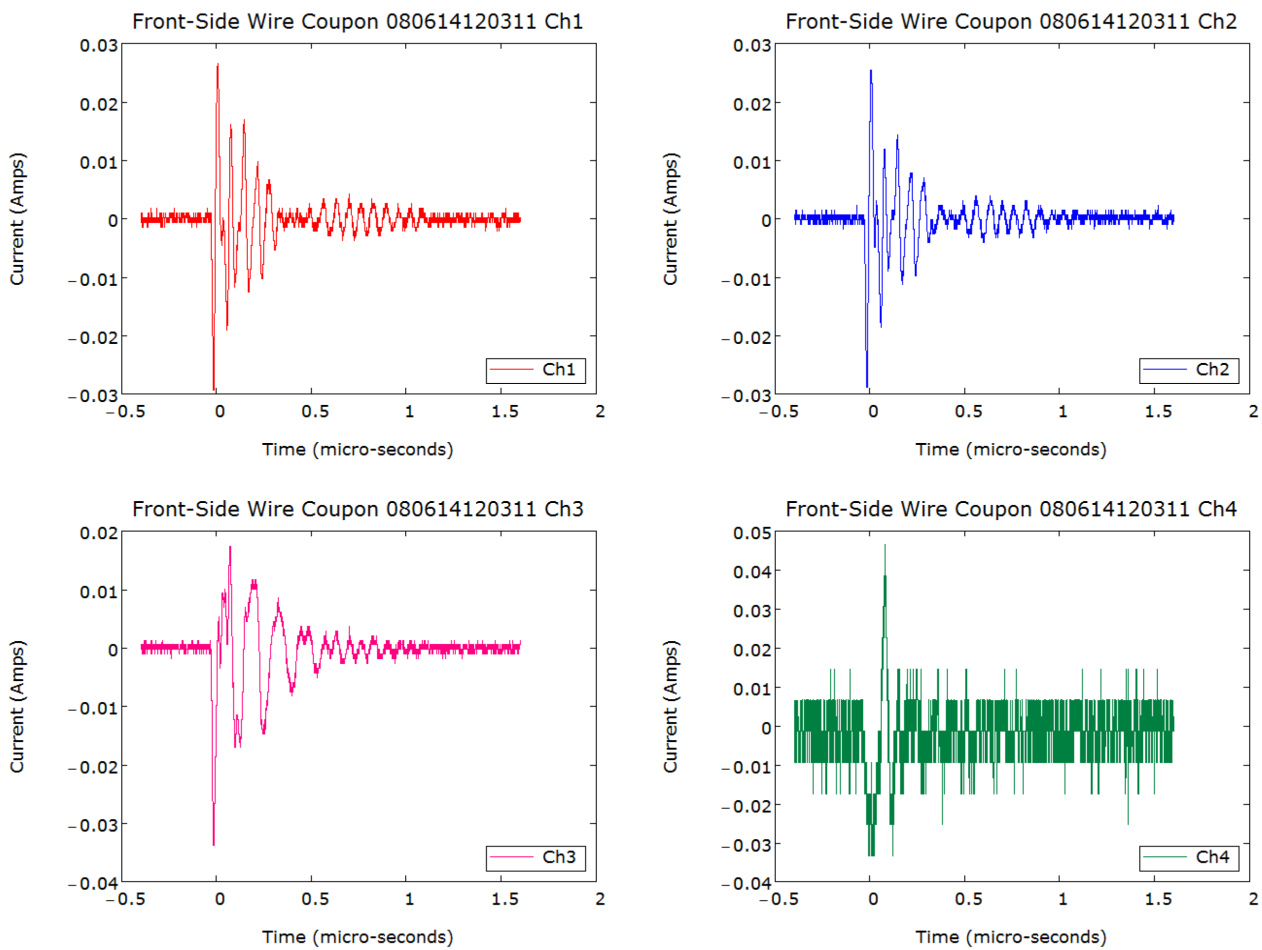
# Anatomy of a Signal that is NOT a Deep Charging ESD Event

**Not a Deep Charging Event**

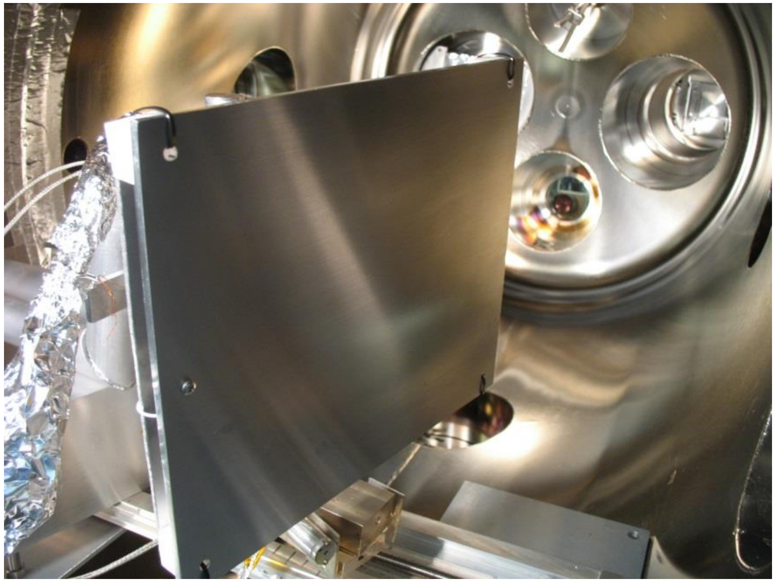
Overall current magnitudes are very low

No unique waveforms

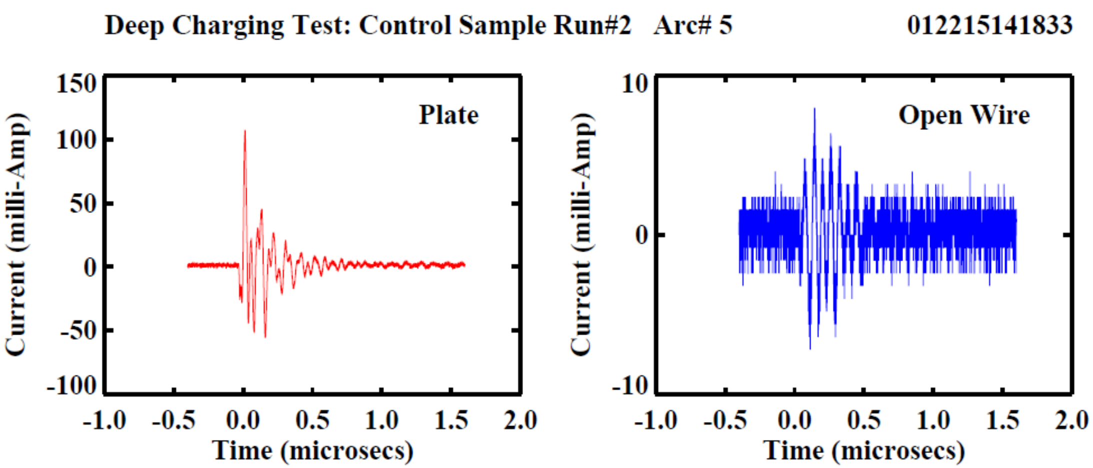
Suspect all signals are induced from a surface discharge elsewhere in the system



# Bare Aluminum Plate Control Test



- Bare Aluminum plate mounted using the same methods as official test coupons
- Any ESD events detected can be ascribed to test setup (chamber) issues
- Useful for finding noise floor



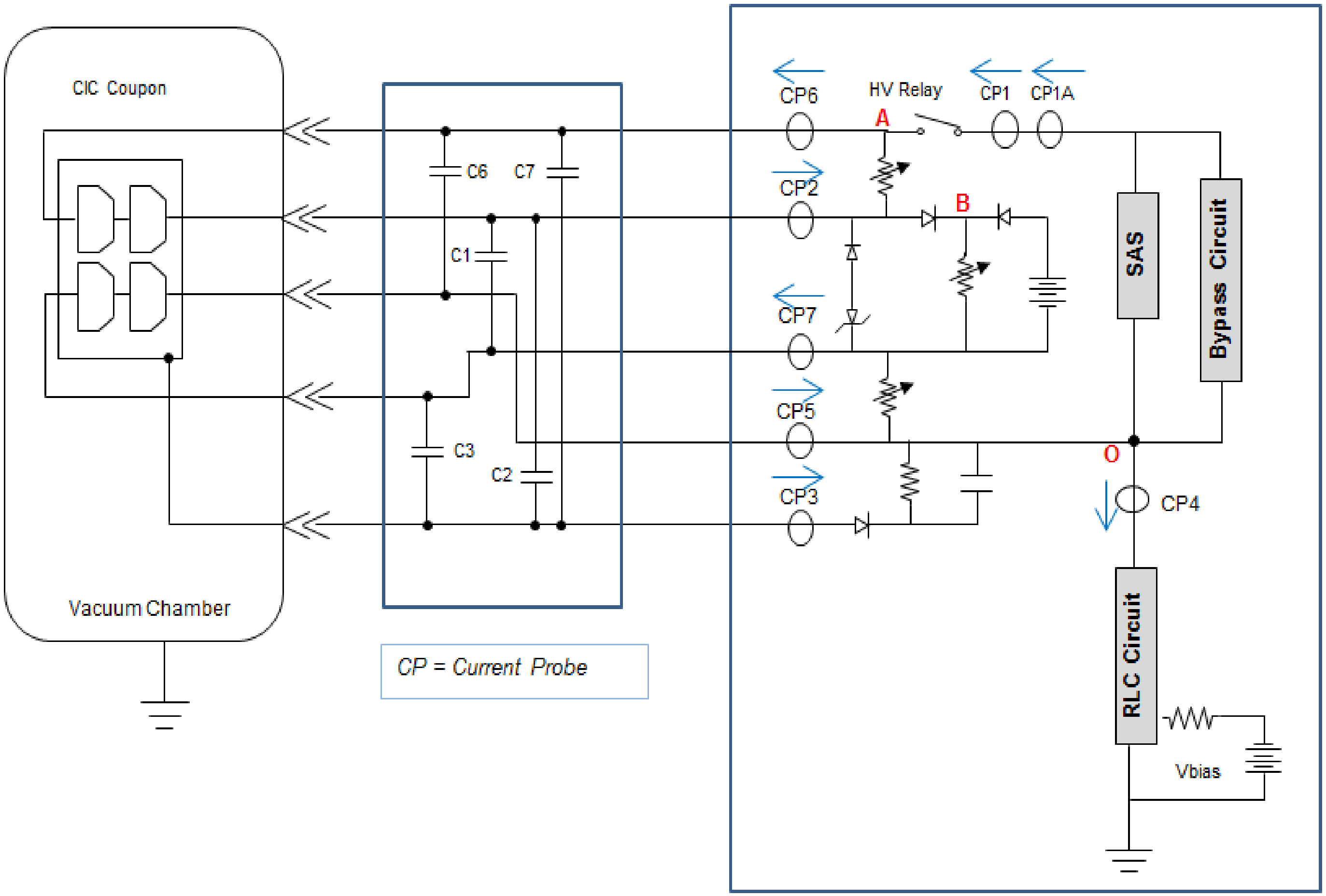

**Typical signals detected by oscilloscope**

**Peak currents of only 100 milli-amps (with considerable ringing)**

**“Open Wire” strictly detects induced noise in the system**

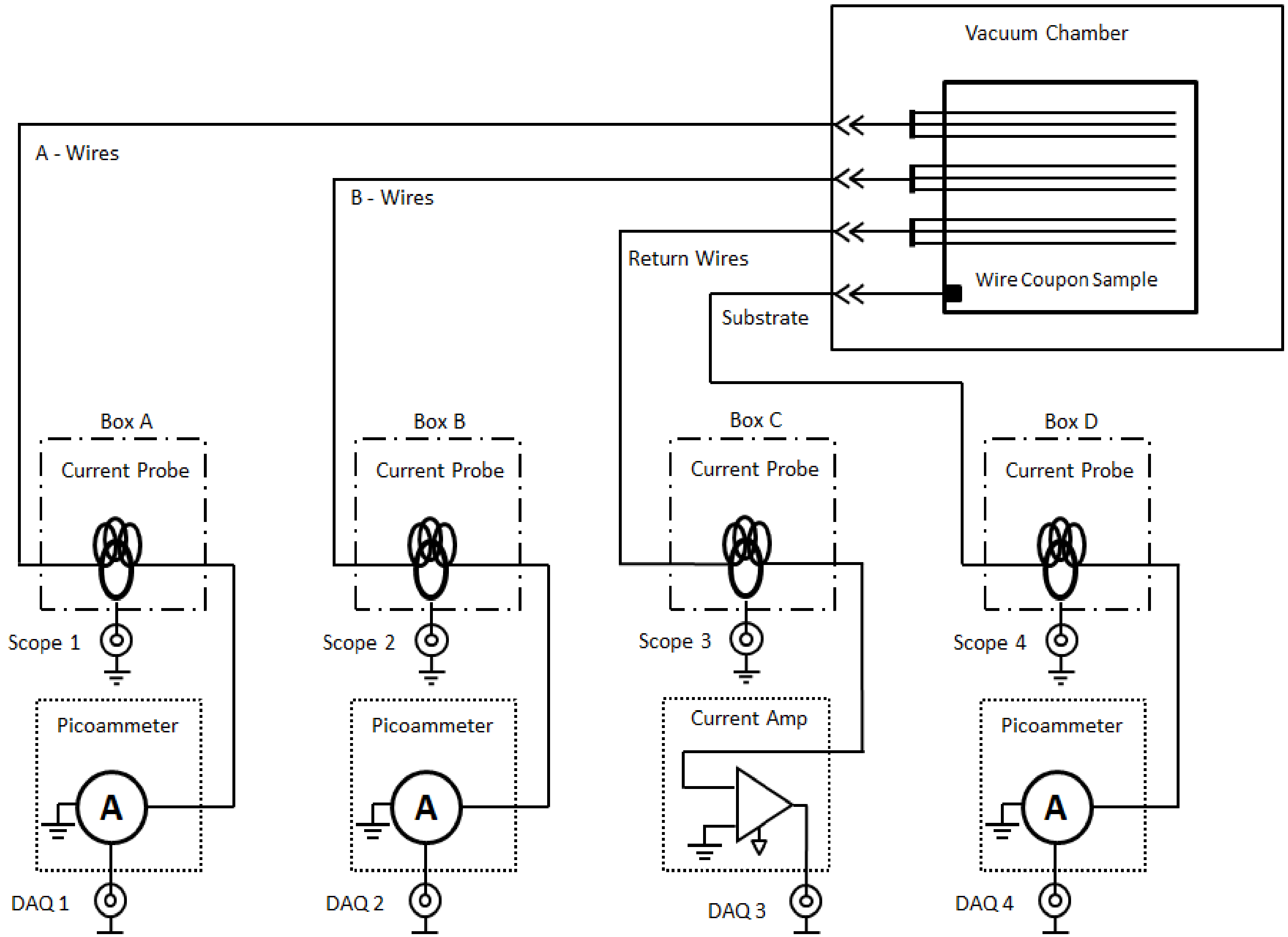
**Provides signal form and magnitude information for effective noise that can be ignored in official coupon tests**

# CIC Coupon Active Circuit Test Setup




**Solar Array Simulator (SAS) power supply reacts quickly to load changes**

# Wire Coupon Passive Circuit Test Schematic




Signal wires were wrapped around the inductive current probes to increase current magnitude sensitivity

# Semi-rigid Coaxial Cable Sample Control Test

- Test of coaxial cable with DC block circuit that includes bleed resistors