Electrostatic Discharge Test of Multi-Junction Solar Array Coupons after Combined Space Environmental Exposures

K. H. Wright (UAH)

T. Schneider, J. Vaughn (NASA/MSFC)

B. Hoang, V. Funderburk, F. Wong, G.Gardiner (SS/L)

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NASA

SPACE SYSTEMS
LORAL

Combined Environment Test Program - Outline

- *Traditional environmental testing of solar array coupons consists of subjecting the coupons to a number of thermal cycles representing the effective mission lifetime.*

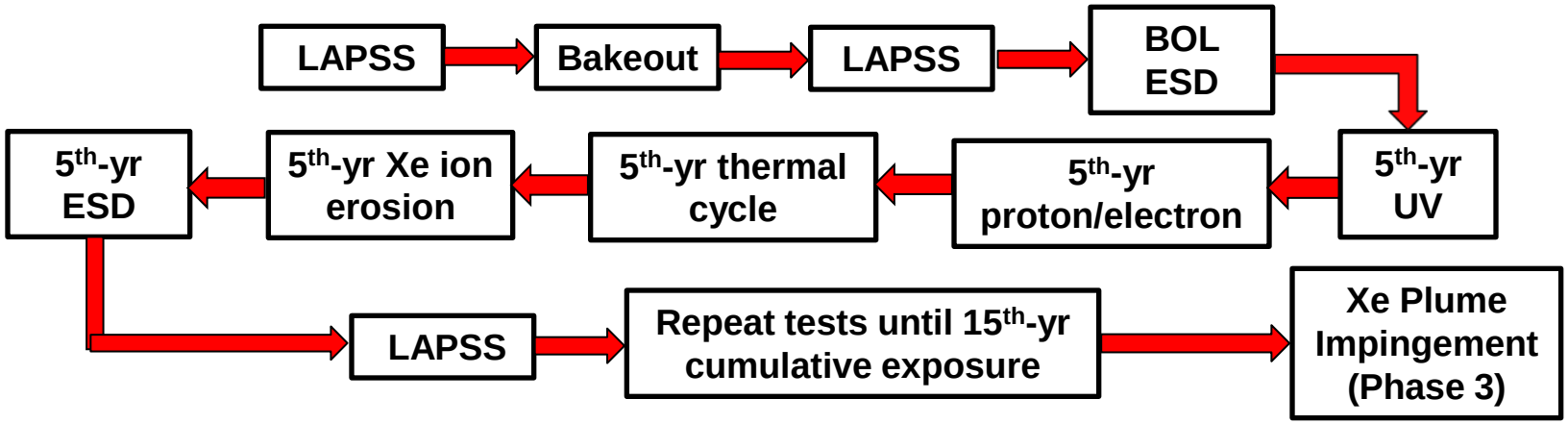
- *Our test program is more ambitious in that solar array coupons will be subjected to a sequence of 5-year increments of <u>combined</u> environmental exposure tests.*

  - ✓ *ESD → UV radiation → electron/proton particle radiation → thermal cycling → ion thruster plume erosion*
    (all tests performed at the NASA/Marshall space Flight Center)

- *Further details of this multi-phase test program are discussed in the poster paper entitled "Combined Space Environmental Exposure Tests of Multi-junction GaAs/Ge Solar Array Coupons" by Hoang et al.*

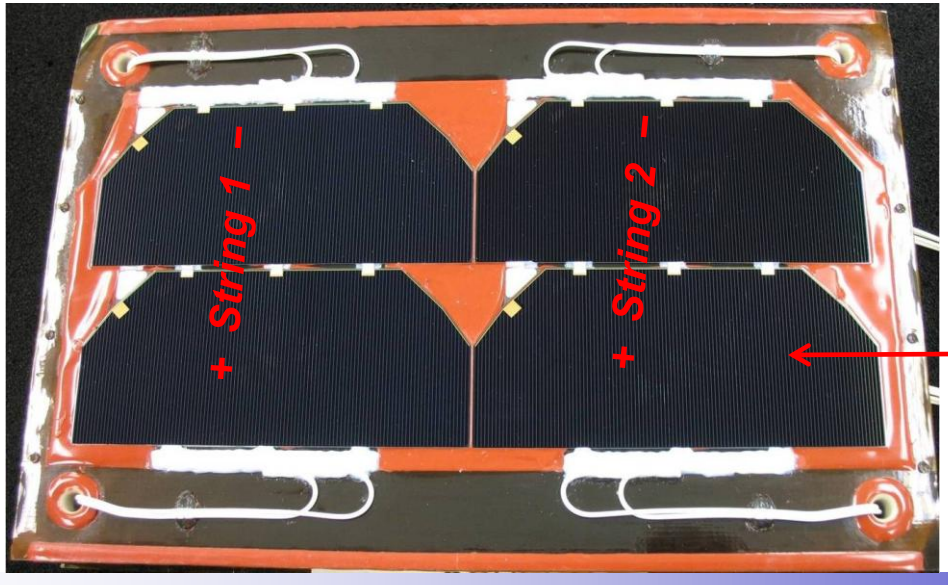
Combined Environment Test Program - Outline

- *The test program consists of multiple phases to examine the cumulative environment effects on both solar cells and solar panel wiring*
- *The discussion in this presentation concerns Phase 2 of the test campaign.*
- *The planned sequence of Phase 2 is as follows:*



Test Coupon Description

- *4 Emcore ATJ GaAs/Ge cells: 2 strings with 2 cells/string. Cell area = 30.49 cm^2.*
- *Coverglass - Qioptiq CMG, 100-µm thick with a single-layer MgF_2 anti-reflective coating.*
- *Each solar cell assembly (SCA) has a discrete Silicon bypass diode.*
- *Coupon size is dictated by the limitation of the radiation facility.*
- *3 coupons used in test program (designated as A, B, and C).*



For Coupon C, this cell is intentionally repaired

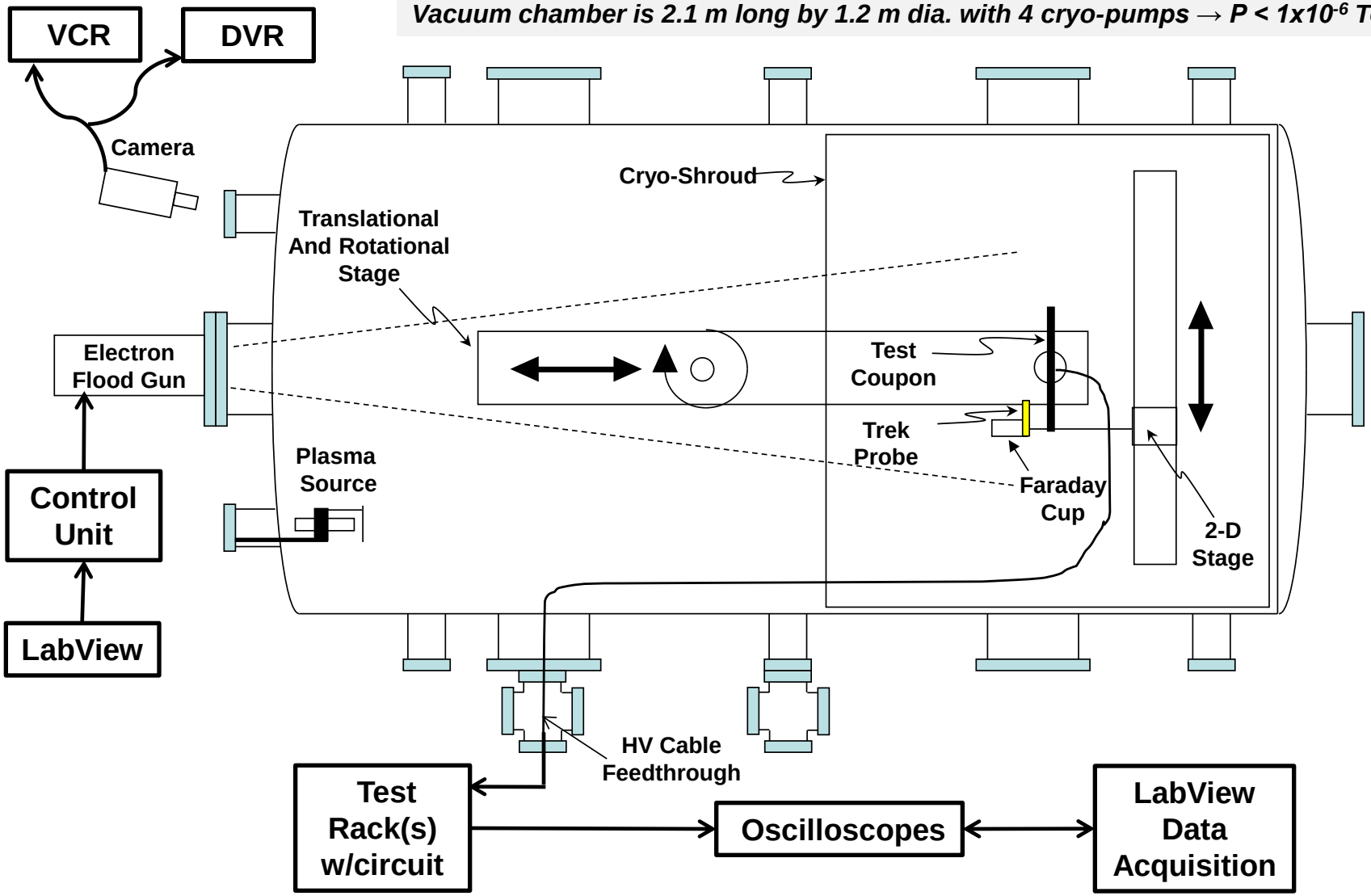
ESD Test: Outline

- *ESD tests are performed at Beginning-of-Life (BOL), 5-year, 10-year, and 15-year (End-of-Life)*
- *Uses guidelines from ISO-11221*
- *Test Conditions:*
  - ✓ *Inverted gradient mode*
  - ✓ *Two differential string voltages: 55 V/0.55 A and 108 V/0.55 A.*
  - ✓ *Limited quantity of arcs through Phase 2 motivated by study of SS/L GEO satellites and number of arcs*

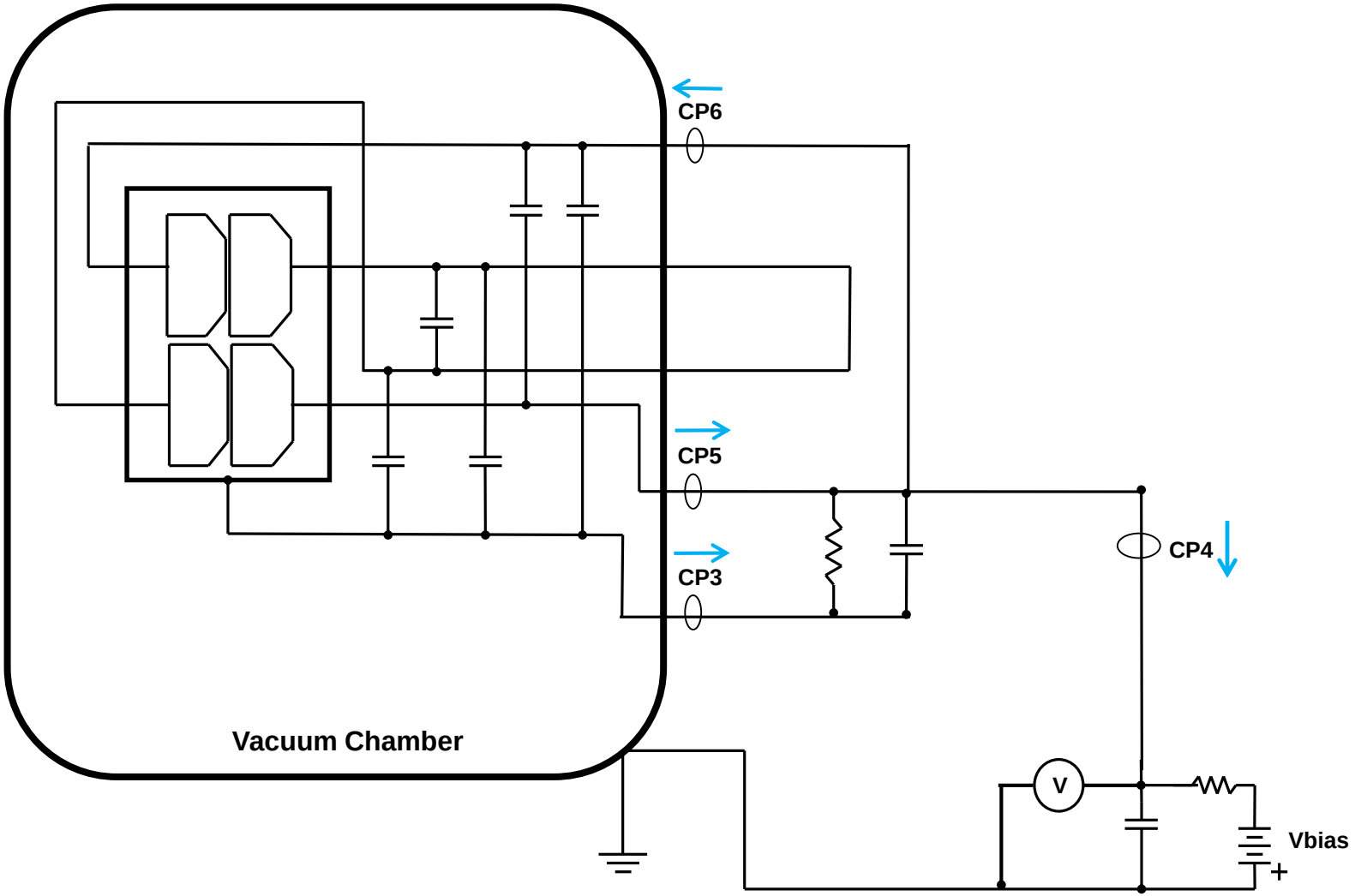
    (Cho et al., Number of arcs estimated on solar array of a geostationary satellite, J. Spacecraft and Rockets, Vol. 42, No. 4, July – August, pp. 640-748, 2005.)
    - *Two arcs in each threshold test*
    - *Five arcs per each differential string voltage in each ESD test (60 total)*

Test Setup Description

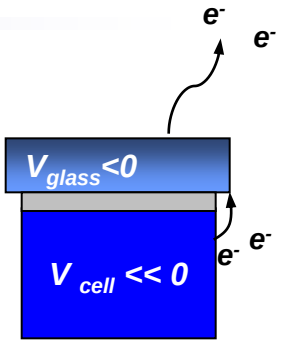
Vacuum chamber is 2.1 m long by 1.2 m dia. with 4 cryo-pumps → P < 1x10^{-6} Torr



Arc Threshold Test Circuit



Arc Threshold Determination

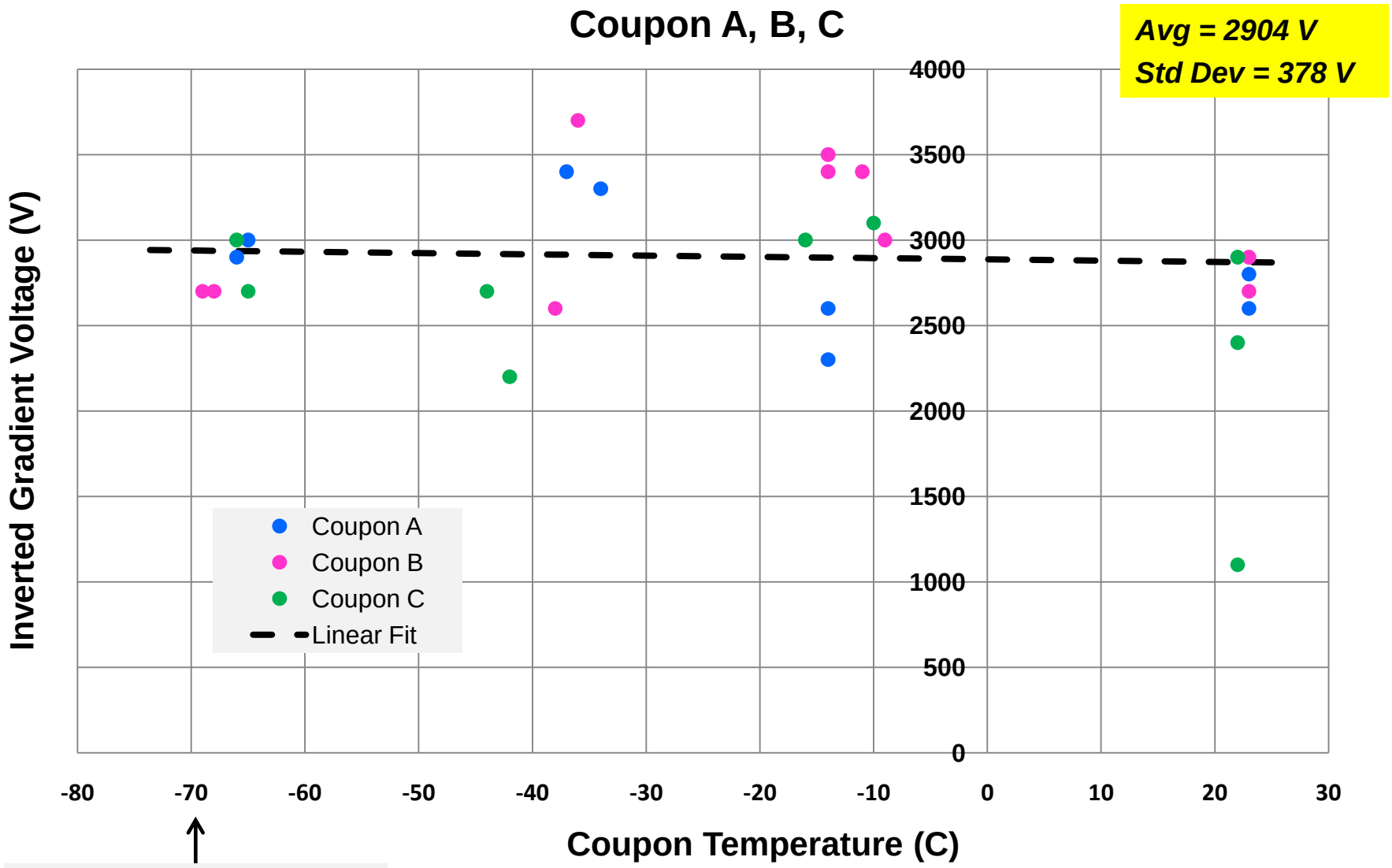


The inverted gradient condition is established by the following:

1) *Apply -5 kV bias to substrate.*
2) *With TREK probe, verify that coverglass is at -5 kV.*
3) *Set electron beam to 5.9 keV.*
4) *Expose coupon to electron beam flux of 1-2 nA/cm^2 for a limited time.*
5) *Measure coverglass potential with TREK probe.*
6) *Set electron beam energy to 900V higher than the magnitude of the coverglass potential.*
7) *Repeat steps 5-7 until arc occurs.*

We are able to control the change in coverglass surface potential by ~ 200 V through this process.

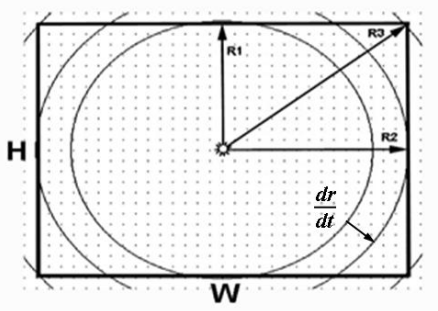
Arc Threshold BOL Results



ESD Test Circuit: Primary Arc Pulse Assumptions

From Hoang et al., Electrostatic discharge test with simulated coverglass flashover for multi-junction GaAs/Ge solar array design, 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii, June 20–25, 2010.

Geometry of Coverglass Flashover from the Center of the Solar Array Panel



Assumptions:

1) ***Coverglass outer surface initially uniformly charged to Voltage (V_c) with respect to solar cell top surface, and discharges by amount deltaV (or V_{th}) during flashover.***
2) ***Flashover current for one panel is assumed to all be collected at a single initiation site.***
3) ***Flashover propagates in a radial surface charge sweep at a constant velocity starting at the initial discharge point.***
4) ***Worst-case peak current is based on complete panel coverglass discharge resulting from a single discharge in the center of the panel. C_{cg} represents the capacitance of the panel coverglass.***
5) ***Flashover terminates at panel edges (R1, R2 and R3) as shown in the figure. Note that R3 ~ 2 meters.***

$$I(t) = dQ/dt = d\,(C_{cg}V_{th}A)/dt$$

$$I(t) = C_{cg}V_{th}\,dA/dt$$

where $A = \pi r^2$

$$I(t) = C_{cg}V_{th}\,d(\pi r^2)/dt = 2\pi C_{cg}V_{th}\,r\,dr/dt$$

where $v = dr/dt$

With the assumption of constant flashover velocity,

$$I(t) = 2\pi C_{cg} V_{th} v^2 t \qquad \textbf{Eq. (1)}$$

ESD Test Circuit: Primary Arc Pulse Analysis

From Hoang et al., Electrostatic discharge test with simulated coverglass flashover for multi-junction GaAs/Ge solar array design, 35th IEEE Photovoltaic Specialists Conference, Honolulu, Hawaii, June 20–25, 2010.

1) *Flashover propagation velocity, v = 10^4 m/s*
2) *Average measured primary arc threshold voltage of SS/L ATJ array design (~ 2 kV from previous tests)*
3) *Calculated panel coverglass capacitance*
4) *Flashover time to R1, R2 and R3 per Figure on Slide 10, based on the SS/L panel geometry*

From Eq. (1):

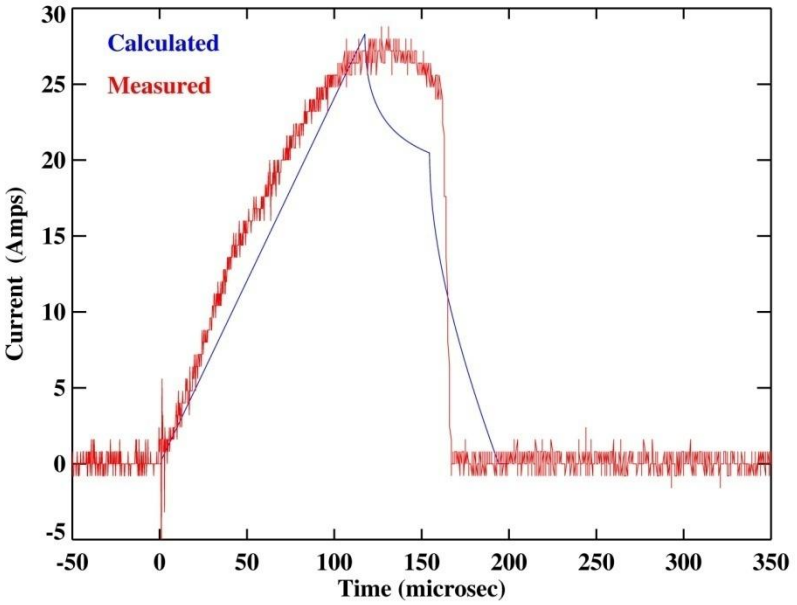
$$I(t_{R1}) = 28.4 Amps$$

(Peak current at R1 as shown in Figure on Slide 10)

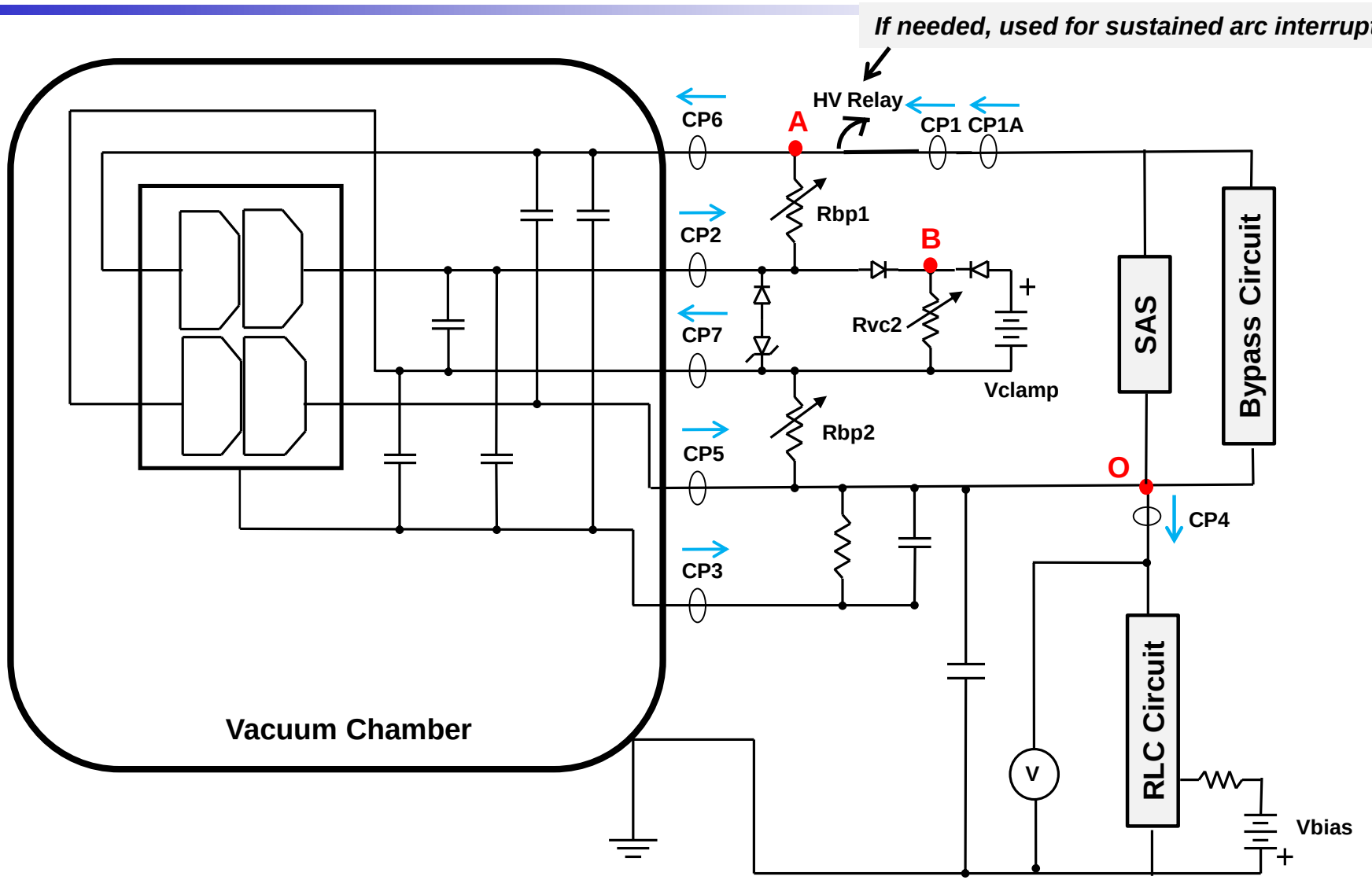
RLC circuit designed to produce waveform that meets three parameters:

1. *Peak current*
2. *Time to peak current*
3. *Total charge of the panel coverglass*

SPICE model calculation compared with measurement of MSFC ESD test circuit:

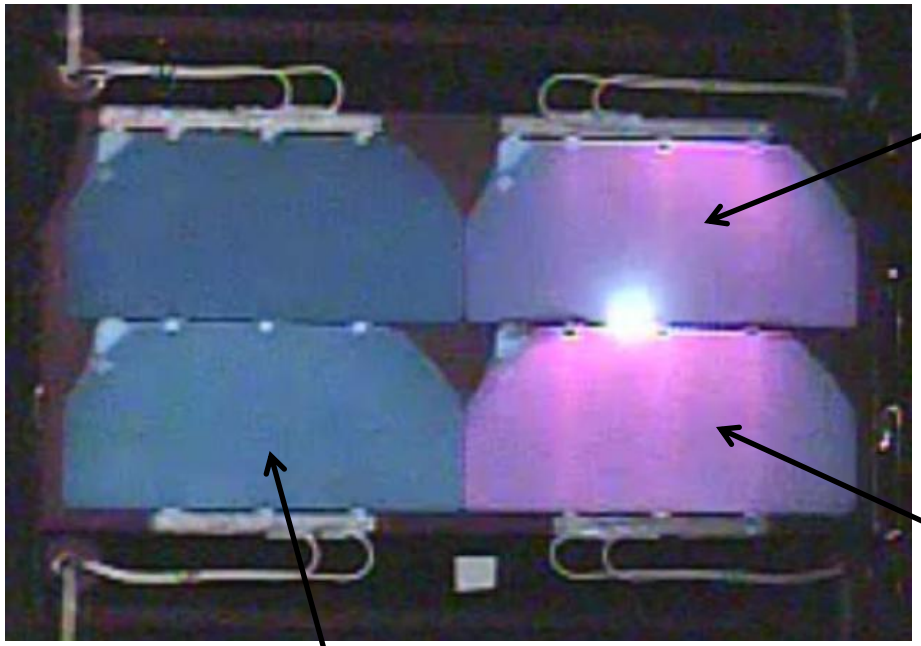


ESD Test Circuit Schematic

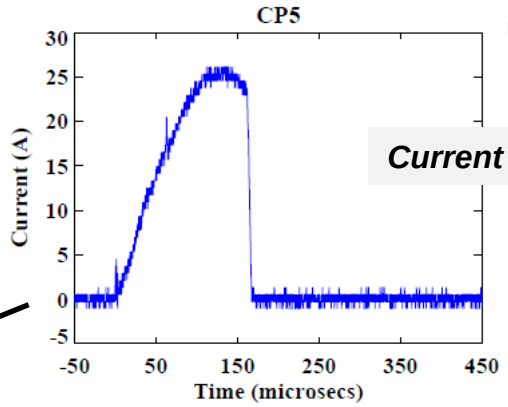


Example of Arc: BOL

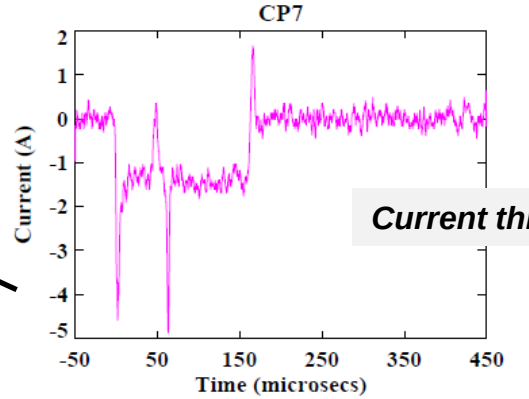
Coupon B: 108V between strings;
Temp = -69C; ΔV ~ 3200V



No activity detected on String-1

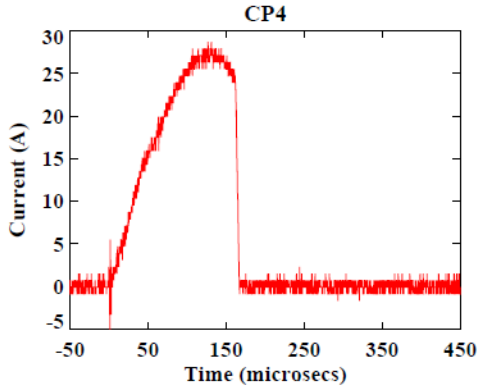


Current through String-2/Cell-2

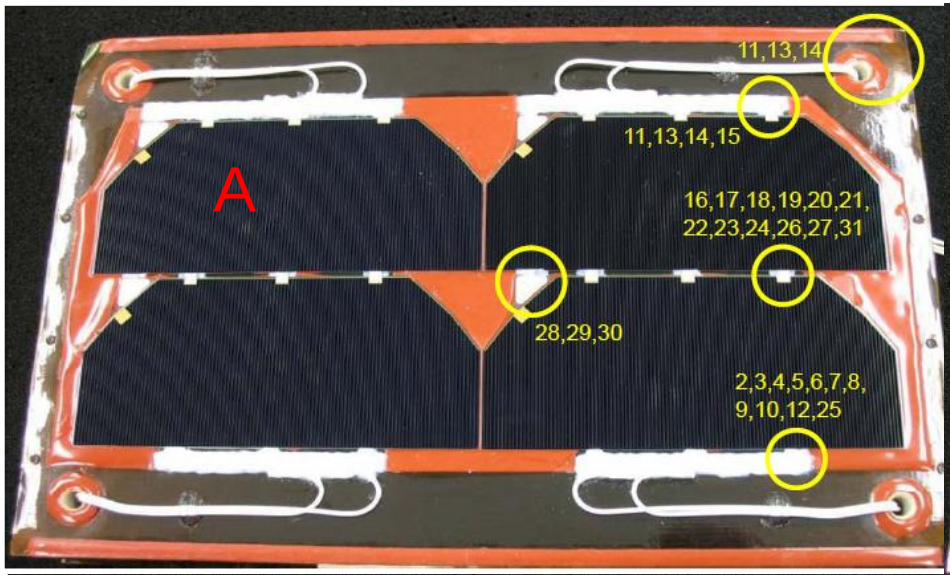


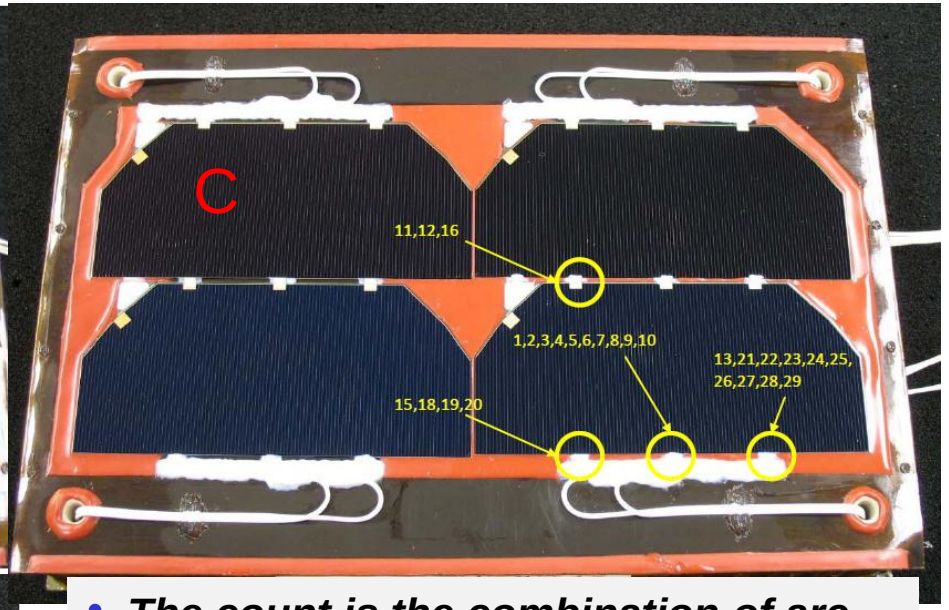
Current through String-2/Cell-1

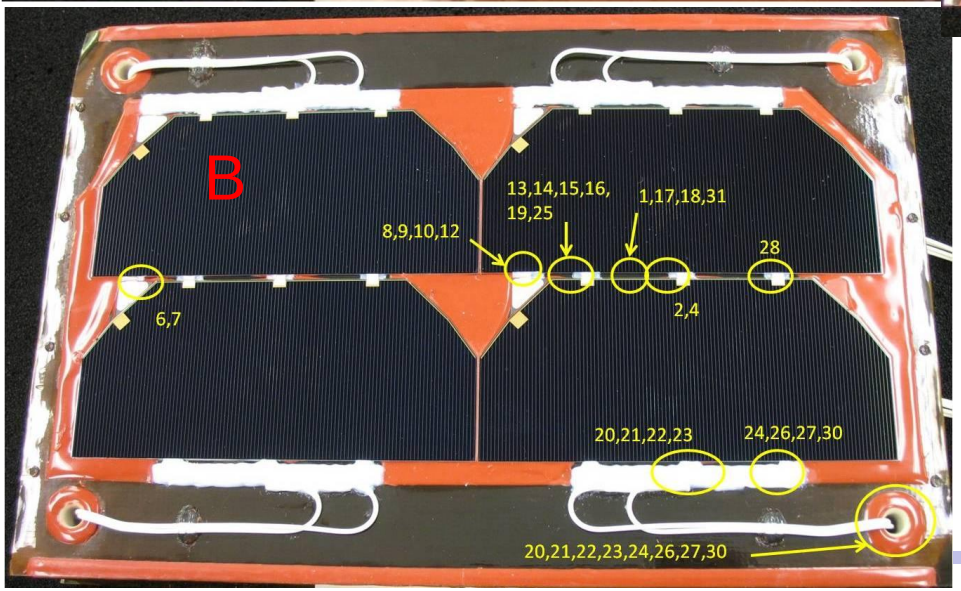
Primary Arc Current



Arc Site Summary: BOL





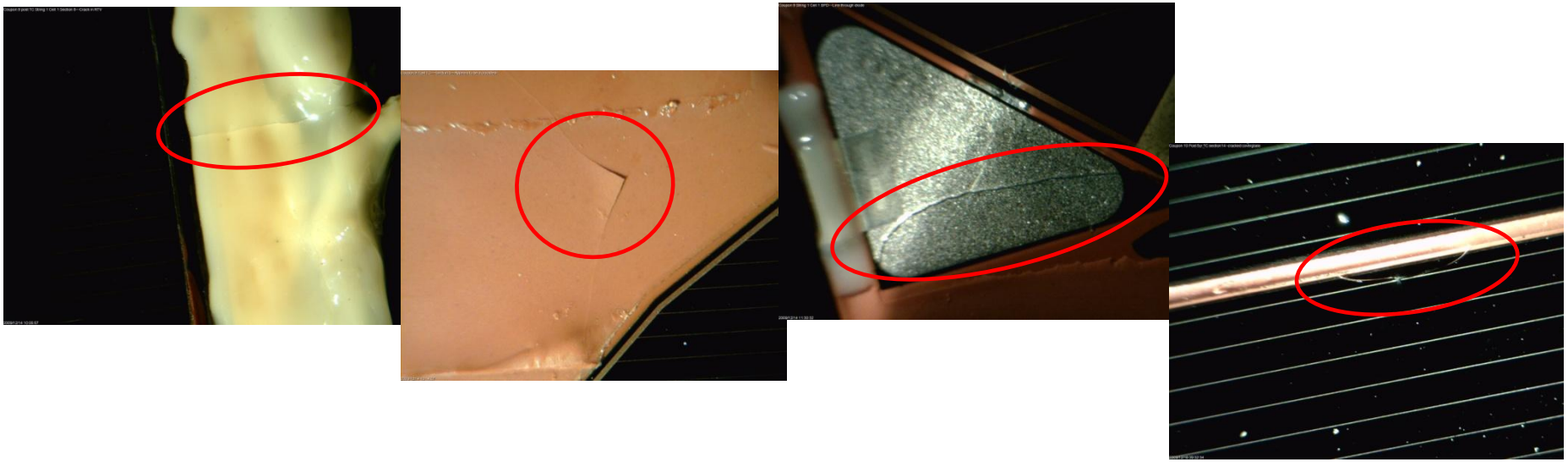


- *The count is the <u>combination of arc threshold and ESD tests</u>*
- *Popular arc sites are cell tabs, busbars, and feed-through bushings*
- *For Coupon C, arc sites favor the reworked cell*

No Temporary Sustained Arcs detected during BOL.

5th-year Test: Status

- 5th-year UV, proton/electron radiation, and thermal cycling tests have been completed
  - ✓ Inspection has shown various cracks in RTV over tabs and busbars and cracks in the grout between cells. Also, cracks on a few of the cell coverglasses are observed.

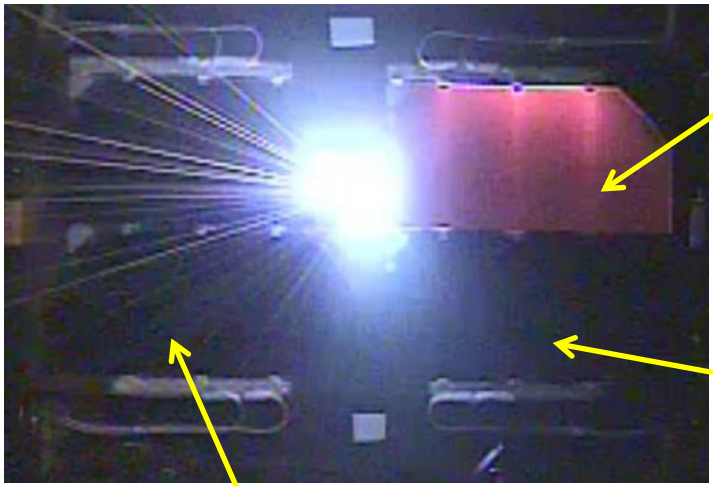


5th-year Test: Status (cont.)

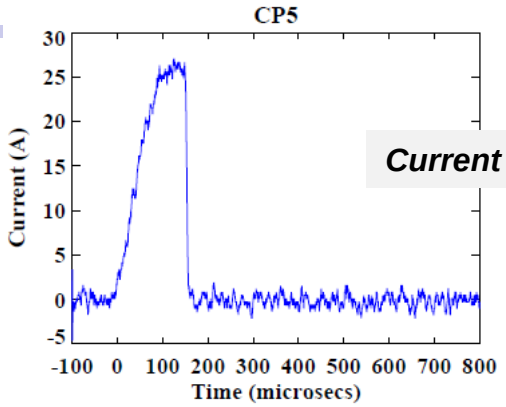
- *Acquisition of a new source for use in the 5-year Xenon ion erosion test is in work.*
- *A slight alteration in the ESD test plan has occurred – partial ESD testing has been performed on each coupon.*
  - ✓ *The arc threshold voltage for each coupon has changed significantly. It is now ~ 200 V! After ion erosion is completed, will this value change?*
  - ✓ *Two arcs at each string differential voltage (55 V and 108 V) have been obtained on each coupon. Arc sites preferentially remain as observed during the BOL testing.*
  - ✓ *After ion erosion is completed, three more ESD arcs will be obtained. The RLC circuit used to simulate the primary arc will remain unchanged from the BOL testing. However, based on arc threshold data, do we change the RLC circuit for future tests?*

Arc at interim 5th-year test point

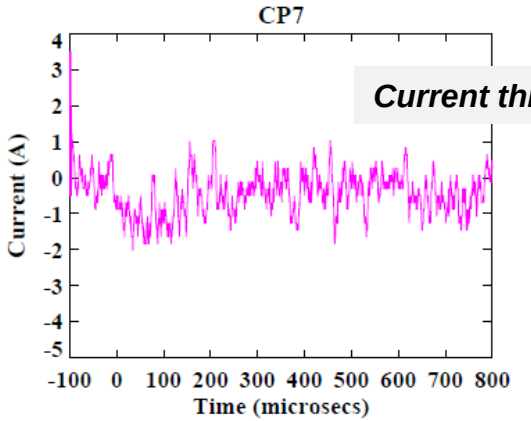
Coupon B: 108V between strings; Temp = 20 C; ΔV ~ 200V



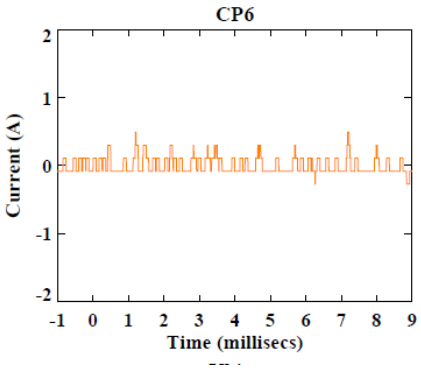
As shown in CP6 and CP2, no activity detected on String-1!

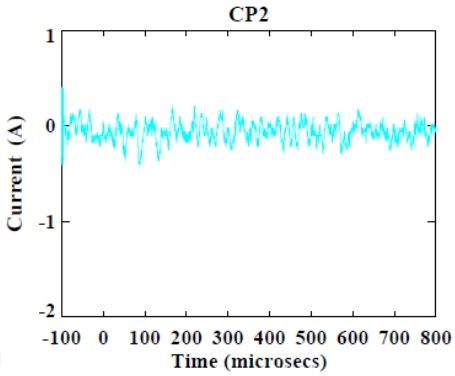


Current through String-2/Cell-2

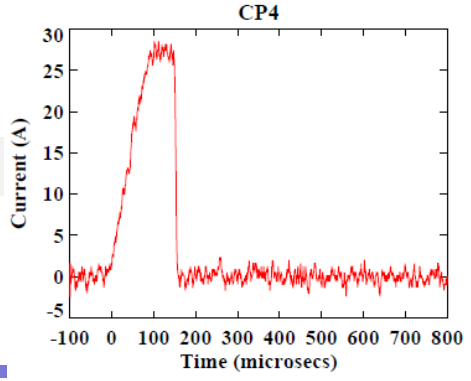


Current through String-2/Cell-1





Primary Arc Current



Key Observations

- *Post 5th-year combined environmental exposures show hairline cracks in the RTV adhesive grout.*
  - ✓ *Although an ESD event occurred at a string-to-string (or parallel) gap, no Temporary (or Permanent) Sustained Arc was observed.*
- *The arc threshold voltage dropped by an order of magnitude after the 5th-year combined environmental exposures.*
  - ✓ *Our present conjecture is that this is due to the effect of the combined environmental exposures.*
  - ✓ *If this observation is true in orbit, then the ESD characteristics of the solar array, such as flashover magnitude and arc frequency, can change over the mission life.*

Forward Work

- *The chamber used for the ESD testing in Phase 2 is also used for ESD testing on another phase of the comprehensive SS/L test campaign involving wire coupons.*
- *Ion Erosion testing is potentially slated for this chamber as well but will most likely be performed in a different chamber.*
- *Scheduling conflicts are driving completion of the 5th-year ESD testing until this fall (2010).*
- *10th- and 15th-year ESD testing is currently planned for early and mid 2011, respectively.*

Based on our preliminary observations of our solar array coupon characteristics, there is an apparent need for further research in material properties as a function of combined space environmental exposures.