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# Electrostatic Discharge Tests for JUICE Photovoltaic Assembly

Francesco Faleg  
Leonardo S.p.A.  
Nerviano, Italy

[francesco.faleg@leonardocompany.com](mailto:francesco.faleg@leonardocompany.com)

Pietro Zanella  
Leonardo S.p.A.  
Nerviano, Italy

[pietro.zanella@leonardocompany.com](mailto:pietro.zanella@leonardocompany.com)

Stefano Riva  
Leonardo S.p.A.  
Nerviano, Italy

[stefano.riva@leonardocompany.com](mailto:stefano.riva@leonardocompany.com)

Paolo Fidanzati  
Leonardo S.p.A.  
Nerviano, Italy

[paolo.fidanzati@leonardocompany.com](mailto:paolo.fidanzati@leonardocompany.com)

Virginie Inguibert  
ONERA  
Toulouse, France

[virginie.inguibert@onera.fr](mailto:virginie.inguibert@onera.fr)

Gael Murat  
ONERA  
Toulouse, France

[gael.murat@onera.fr](mailto:gael.murat@onera.fr)

**Abstract**—In the framework of JUICE Photovoltaic Assembly, development and testing activities have been carried out in order to verify the effectiveness of grounding networks solution against ESDs occurrence in charging environment. During prequalification phase, dedicated coupons have been manufactured and submitted to environmental test campaigns, including ESD characterization. As the PVA design has progressed, a new ESD coupon with more representative technologies has been then manufactured and tested for electrons charging, so to compare results and assess new design and materials. This paper firstly describes the coupons manufactured for ESD testing, then an overview on ESD characterizations performed is provided. Lastly, relevant conclusions and comparisons between the results are discussed.

## I. INTRODUCTION

JUICE spacecraft is going to orbit around Jupiter and its satellites, in a very hostile environment: in addition to cryogenic temperatures and low illumination, the Photovoltaic Assembly in particular is going to be subjected to low energy electrons flux, which will cause charging of dielectric materials on it. In order to avoid differential charging and its detrimental effects, like electrostatic discharges creating electrical shunts on solar cells, a tailored design has been developed for the solar array: in compliance with the requirement of having 1 V maximum voltage bias between any two points of the solar array, ITO coated coverglasses and coverglasses grounding network have been selected for the final design of the PVA front side, together with conductive surfaces and materials on the panel's rear side. As part of the development phase and of the qualification one, Leonardo has tested different design solutions by manufacturing PVA coupons, which have been then tested by ONERA to verify the effectiveness of the selected solutions in charging environment.

## II. PRE-QUALIFICATION TEST

In the framework of B1 phase, Leonardo manufactured ESDs coupons, that were meant to test ESD susceptibility of two different PVA designs; ESD tests were performed on both on BOL and EOL coupons sharing the same layout, in order to also assess the effect of thermal ageing of the grounding network. The coupon design was such to have a two-strings layout configuration with offset, while grounding network on coverglasses was realized by means of squared patches made of a silicone conductive mesh. For the purpose of clarity, hereafter the coupon representative

for BOL will be indicated as A1 and the coupon submitted to complete cycling (EOL) will be indicated as A2.

A picture of the coupon A1 is presented in Figure 1: it is remarked that the coupons were manufactured by ensuring an interstring gap of 0.5 mm between the 2 strings, as a worst case for secondary arcing occurrence.

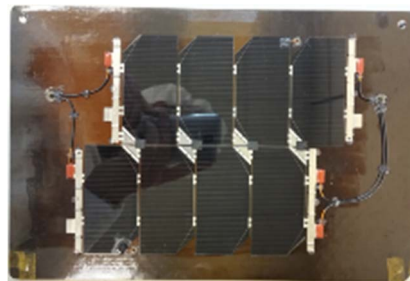


Figure 1 – Pre-qualification coupons layout

An overview of the tests to which the coupons were submitted is presented in Table 1.

Table 1 – High level test sequence for prequalification coupons

Test	Coupon A1	Coupon A2
Bake-out	24 h at +95°C , 72 h at +125 °C	24 h at +95°C , 72 h at +125 °C
ESD BOL	YES	-
TV cycling	-	~ 180 cycles with $T_{min}$ and $T_{max}$ in the range [-235 °C; +110 °C]
ESD EOL	-	YES

The ESD tests were performed by ONERA in their JONAS vacuum facility, where the following characterizations took place:

- Primary arcs test under plasma flux

- Primary arcs test under electrons flux
- Secondary arcs test under plasma flux

Aim of the primary arcs tests were to highlight which materials of the coupon were more subjected to charging and to identify locations where Inverted Potential Gradient (IPG) was established. In Figure 3, a schematic of the set-up used by ONERA is presented.

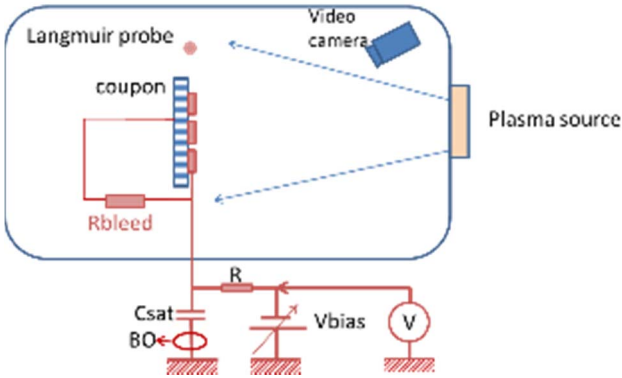


Figure 2 – Set-up in JONAS facility with plasma source

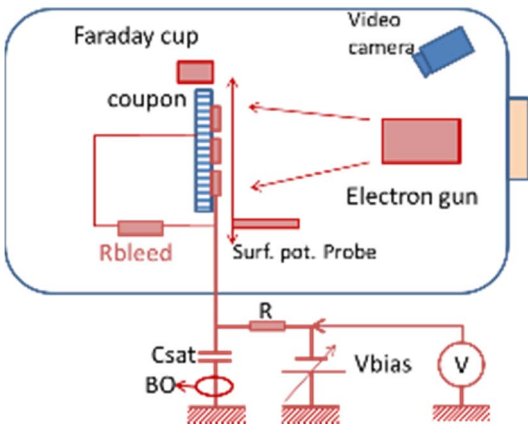


Figure 3 Set-up in JONAS facility with electron source

Although JUICE mission is not operating in LEO environment, which from ESD test point of view is well simulated by plasma source, this kind of test was performed in order to achieve reasonable number of ESDs and to record their position.

For the electrons irradiation test, the goal was to create a set-up representative for Jovian environment: for this reason the electron current density on the coupon was chosen equal to 12 nA/cm<sup>2</sup>, a conservative value which was however derived from worst case requirement conservatively margined. Coupon was biased to -5 kV and electron beam set to 5.5 keV, to maximize the secondary electron emission yield and establish IPG on coverglasses.

Specifically, the major outcome of the primary arcs test under electron flux was that ESDs were mainly concentrated on the following locations on the coupon:

- Solar cells edges exposed to the kapton surface surrounding the two strings
- Triple points due to the presence of siliconic resins (dielectric) and bus-bars (metals)
- Grounding patches on coverglasses: the occurrence of ESDs on some of them has been explained by the presence of exposed dielectric structural fibers that were embedded on the conductive silicon. Only few ESDs were observed on these patches anyhow

As additional important output of this workpackage, a voltage probe was scanned close to the surface of the coupon's PVA after irradiation's runs, in order to verify the grounding network's effectiveness in keeping the coverglasses potential equal to the one of the coupon's substrate (-5 kV). The result of such scanning on coupon A1 is presented in Figure 4, where it is possible to appreciate that the potential measured close to the coverglasses was indeed -5 kV, without deviations along the whole length of the strings. Similar plot was obtained for coupon A2. Higher potential was measured out of the strings and in particular on the exposed kapton surface, as expected.

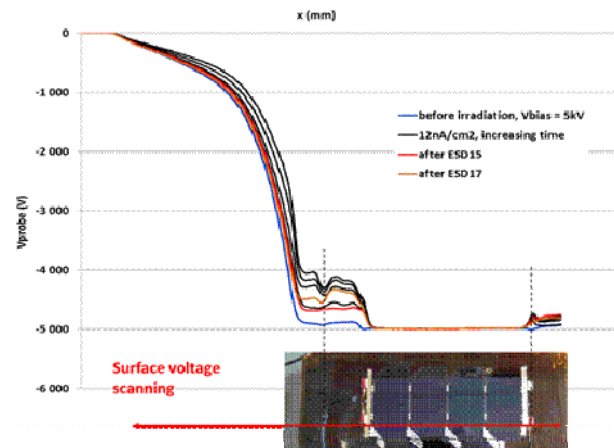


Figure 4 – Voltage probe measurement on pre-qualification coupon

After each test, dark IV curve of both strings was characterized and insulation between substrate and strings was measured as well: no difference or deviation was observed, meaning that ESDs had not degraded the cells.

Following step, after primary arcs testing, consisted in biasing the strings in order to check the current-voltage combination needed to trigger secondary arcs on the coupon. The set-up illustrated in Figure 5 was used: by means of a Solar Array Simulator, strings were biased in order to achieve different voltage-current combinations, covering different mission phases of JUICE; current was set to progressively increasing values, starting from very low values (20 mA) up to 0.5 A. Capacitance values were chosen to correctly represent the presence of the remaining strings on the complete solar array. Test was performed in

plasma environment because of the higher ESDs rate deriving by the use of this charging source.

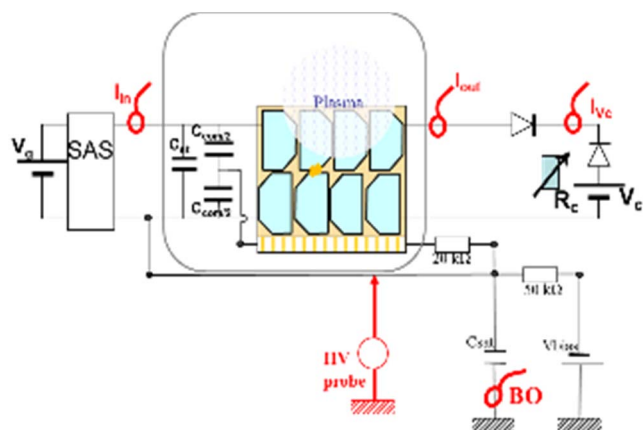


Figure 5 – Schematics of test set-up for secondary arcs test

As well known by literature [1], no secondary arcs are expected for voltages-currents settings lower than 150 V-0.5 V, in the case of 0.5 mm inter-string gaps: indeed, this was experimentally confirmed on both A1 and A2 coupons, where no secondary arc was detected and observed for JUICE typical current parameters. As purely scientific characterization, it was decided to cover the ITO coated coverglasses with kapton foil and to force a secondary arc in the string gap: it was eventually triggered only at maximum voltage and current (150 V, 0.5 A) a Non Sustained Arc (duration equal or shorter than primary discharge), that did not result in any impact on the dark IV curve of both strings. It is important to remark that these high current and voltage parameters are not applicable to JUICE mission and in this final test grounding network was indeed prevented from operating nominally.

To summarize, main results and conclusions from pre-qualification ESD tests were the following:

- From ESD test point of view, no difference was observed between coupons that had been submitted or not to TV cryogenic cycling
- No degradation of dark IV curves at string level was observed on both coupons after exposure to plasma source, to electrons beam and after secondary arcs test.
- ESDs have been discovered to occur on several locations of the coupons. Most typical ones, for electrons irradiation, are shown in Figure 6

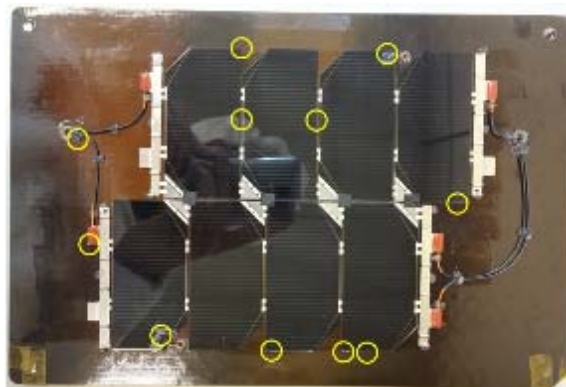


Figure 6 – ESDs locations on pre-qualification coupons

- Some ESDs were observed in correspondence of coverglass grounding network patches, highlighting a possible issue deriving from the intrinsic structure of the conductive adhesive mesh.
- The voltage probe scanning on the surface of the coupon successfully demonstrated the effectiveness of the grounding network in keeping coverglasses at the same potential of the substrate.

### III. VALIDATION COUPON TEST

As the development phase of JUICE PVA progressed, some of the key technologies have been modified or newly designed. On the PVA, the focus of a major improvement has been the grounding network that connects the coverglasses to the rear side: instead of conductive adhesive patches, a metallic wire running on the coverglasses has been preferred [2], so to increase reliability and effectiveness of electrical grounding. Also on the substrate rear side, solar array prime contractor Airbus D&S Netherlands, has chosen a design in which black kapton is applied on the carbon fiber skin [3]. Pictures of the front and rear side of this coupon are presented on Figure 8. Because of these major changes and other minor design modifications, ESD test has been repeated to validate such technologies for electric charging behavior.

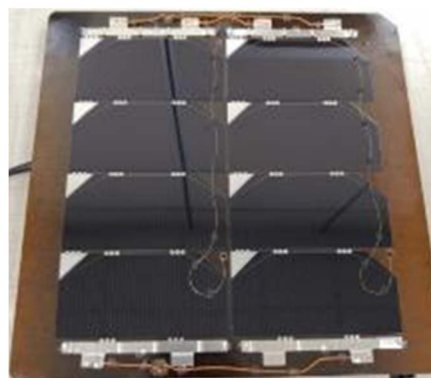


Figure 7 - ESD validation coupon's front side



Figure 8 – ESD validation coupon's rear side

The coupon, after manufacturing, has been submitted to bake-out (24 hours at +95°C followed by 72 hours at +125 °C) and then to a standard set of inspections and checks, as ELM and thermographic inspection. Electrical checks have been performed, including electrical performances measurements by means of flasher test in Low Intensity Room Temperature (LIRT) conditions.

In view of the experience acquired during the pre-qualification phase, this second ESD test has been limited to the following characterizations:

- Primary arcs test of the coupon's front side under electrons irradiation
- Primary arcs test of the coupon's rear side under electrons irradiation

The same set-up presented in Figure 3 has been used by ONERA, biasing the coupon substrate to  $-5$  kV and irradiating the coupon surface with a 5.5 keV electron beam, with current density of  $12$  nA/cm<sup>2</sup>. The lateral sides of the coupon have been shielded with Al foil in order to prevent ESDs to occur only on honeycomb's edges.

After each step, dark IV curve of each string has been measured, as well as insulation between strings and substrate, in order to verify that no electrical degradation occurred due to ESDs.

Hereafter focus is put on results regarding irradiation on front side, which is a more critical for the PVA than the rear side. On Figure 10, the positions of ESDs recorded during the 4 hours test are presented: in red circles ESDs are highlighted in case their number has resulted to be higher than 10, in yellow circles discharges occurring less than 2 times during the irradiation time.

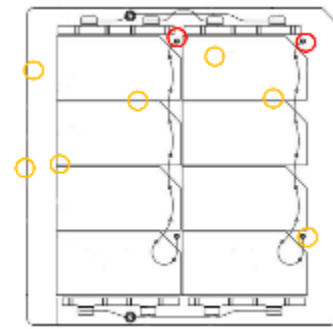


Figure 9 – Schematics of ESDs positions on front side

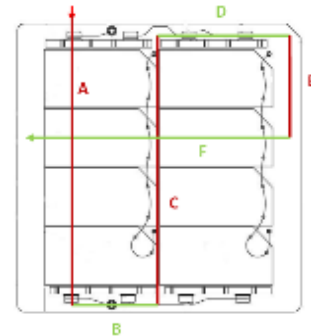


Figure 10 - Schematics of voltage probe scanning path on front side

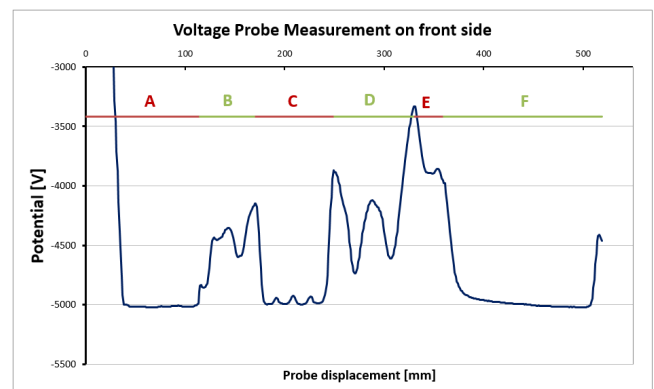


Figure 11 – Voltage probe measurements on front side

Voltage probe scanning has been performed following a x-y path indicated in Figure 10 and the associated results in terms of measured voltage are plotted in Figure 11; it can be recognized, on paths A, C and F, that the voltage measured in proximity of the ITO coated coverglasses is in fact equal to  $-5$  kV, demonstrating that no IPG is established on coverglasses or on the grounding network. On path C, small fluctuations that are visible are due to the kapton left exposed on the 3 crop-corners between the two different strings. ESDs are concentrated in correspondence of the two feedthrough holes through which the grounding metallic wire is routed to the rear side: this is explained by the presence of small bushings, that are made of dielectric material, close to the metallic grounding wire. It is worth to mention that, after 4 hours irradiation, ESDs rate decreased by a factor of 5, maintaining a decreasing trend, due to the vaporization of sharp tips that were the location of the cathodic spots.



Similar tests have been repeated by irradiating the coupon rear side again with an electron flux equal to  $12 \text{ nA/cm}^2$ . Figure 12 shows the path followed by the voltage probe after irradiation step, while the actual reading is presented in Figure 13. The signal plotted corresponds to the potential bias, where 0 V is the reference ground of the substrate's core. It can be observed that potential is varying significantly: in correspondence of conductive surfaces it is uniform and close to ground, as expected, while IPG occurs in presence of the unavoidable dielectric insulators that are needed for the PVA to nominally operate.

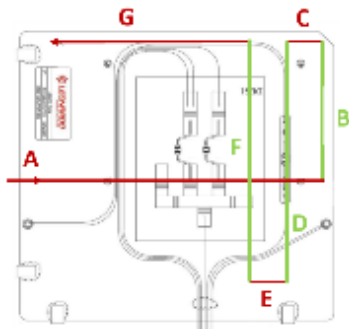


Figure 12 – Schematics of voltage probe scanning on rear side

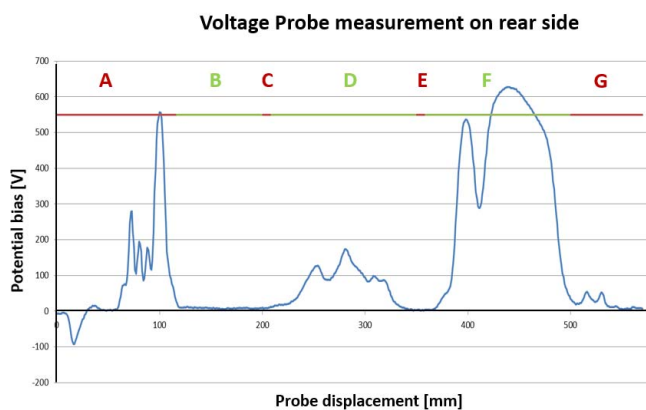


Figure 13 – Voltage probe measurement on rear side

No deviations on dark IV curve of strings, insulations anomalies or visual defects were detected after irradiation steps. At the time this paper is submitted, a full set of final electrical characterizations are going to be performed on the coupon at Leonardo, including LIRT measurements; nevertheless, the following conclusions on this test can be drawn:

- It has been successfully verified that the new concept for grounding network, using a metallic wire bonded on coverglasses, is effective in keeping the potential of coverglasses equal to the one of the substrate's honeycomb and of the rear side, as confirmed by the voltage probe measurements
- ESDs that have been detected are mostly concentrated on positions that are not critical for the PVA operation
- In general, ESDs number and rate recorded on the front side of this coupon are lower with respect to the ESDs

triggered during tests on pre-qualification coupons, using same set-up and parameters

- No dark IV curves degradation, insulation issues and defects have been introduced by the test

#### IV. CONCLUSIONS

As critical input for the JUICE PVA project, dedicated coupons have been manufactured by Leonardo and tested by ONERA for assessment on their sensitivity to ESDs. Two different test campaigns have been necessary to verify the PVA grounding technologies at different stages of development. Pre-qualifications ESD coupons mainly demonstrated that ageing due to cryogenic thermal cycling is not playing a role in the response behavior to an electrostatic charging environment; coverglasses grounding network concepts have been identified and improved, eventually demonstrating the effectiveness in keeping coverglasses at the same potential with respect to the substrate's electrical ground. ESD test on flight representative hardware has also demonstrated the suitability of selected technologies in mitigating ESDs' occurrence on the front side of the PVA, so to avoid shunts and therefore detrimental effects on solar cells operating in low illumination conditions.

#### ACKNOWLEDGMENT

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