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ELECTRO STATIC DISCHARGE TESTING ON METEOSAT 3RD GENERATION PHOTOVOLTAIC ASSEMBLY

Giulia Damonte [(1)], Giorgio Saltanocchi [(1)], Pietro Zanella [(1)], Emanuele Ferrando [(1)], Stefano Riva [(1)], Gianfranco Meniconi [(2)], Damiano Pagano [(2)], Fabrizio Scortecci [(2)]

[(1)] *Leonardo Company, Viale Europa s.n.c., 20014 Nerviano (Mi), Italy, Email: giulia.damonte@leonardocompany.com*
[(2)] *Aerospazio Tecnologie, Strada di Ficaiole, 53040 Rapolano Terme (Si), Italy, Email: fscortecci@aerospazio.com*

ABSTRACT

The electrostatic discharge testing on Photovoltaic Assemblies has been thoroughly investigated and performed during the last decade to ensure durability of solar arrays, especially in cases of high power satellites. *Leonardo Company* together with *Aerospazio Tecnologie* performed the test for the first time in the framework of Meteosat Third Generation (MTG, a Geostationary satellite of 2.5kW, mounting 3G solar cells) with two goals: the first was to qualify MTG PVA technology against possible ESD occurrences during mission and the second was to characterize the PVA design limits against self-sustained arcs.
This paper illustrates the ESD analysis, the test set up preparation and the test results obtained in the framework of MTG ESD test campaign.

1 UNDERSTANDING OF THE ESD PHENOMENA

Space environment substorms can generate Inverted Voltage Gradient (IVG) on solar arrays: the satellite body and solar arrays substrate charges up to several kilovolts compared to the space environment, while dielectric parts (mainly solar cells coverglasses) build up a differential charge of the order of hundreds of Volts by the effect of a different rate of emissions of secondary and photo electrons.
When the electric field generated by the different surface potentials exceeds the threshold value, the satellite capacitance is discharged (blow off), leading also to the release of the charge stored in the solar panels dielectric surfaces (flashover), i.e. solar cells coverglasses and insulation sheet. Since the capacitance of spacecraft (on the order of one hundred pF) is not as great as the capacitance of the dielectric surfaces (of the order of µF), the flashover discharge is the major current source of electrostatic discharge. Flashover discharges depends on the plasma velocity and propagation area [2]; in the ESD testing it is simulated through an external capacitance, dimensioned in order to provide the same energy stored on cover-glasses during mission [4].

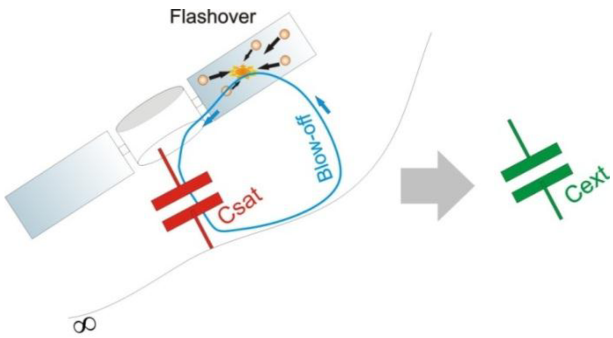

Figure 1: Blow off and flashover impression

The primary discharge generates local plasma environment by vaporization of metal materials at the discharge site, creating a temporary conductive path that can lead to secondary arcs, powered by polarized parts, as can be solar array strings. In case of sufficiently high voltage / current values (typically > 50V / 2A), the secondary arcs in the inter-string area can be self-sustained by the Solar Array power, collecting a string current or even a section current, if no blocking diodes are adopted at string level. Self-sustained arcs can seriously damage the PVA and its insulation layer at the arc site.

2 ESD HAZARD FOR MTG MISSION

MTG PVA shows a strong design against ESD phenomena for the relatively low levels of operating current and voltages, for strings and sections disposition on the panels and for the adopted materials:

- All the metallic parts on the substrate that are not part of the power generation net are grounded to the substrate
- All metallic parts that are part of the Solar panel structure and deployment system are grounded to the satellite through a wires grounding net
- The adopted wires have antistatic external jacket, grounded throughout the substrate surface.
- Blocking diodes protect each single string
- Strings voltage and current levels are quite low (less than 110 V and 600mA during the whole mission in nominal and failure cases)
- Strings and sections are disposed on the panels in a way that maximizes the inter-section gaps (> 5mm) and the inter-strings gaps (> 0.5mm) and that minimizes the voltage differences between adjacent

cells in all nominal (< 50V) and failure cases (< 110V).

This said, the main interest of the present test campaign is in the sustained arc threshold characterization phase more than in MTG ESD qualification phase, which was quite certain to be completed in a successful way since the beginning.

The MTG qualification phase test parameters were chosen between the maximum voltage / current combination encountered during mission in all nominal and failure cases (see Table 1). It is important to notify that the failure cases listed in Table 1 reflect voltage / current combination that occur only in string interruption cases, which, in practice, could hardly lead to sustained arcs. The choice of this test parameters followed a conservative approach and provides an ulterior margin to the results exposed in paragraph 5.

Table 1: Mission Voltage / Current for MTG ESD qualification

Case	Maximum Inter-cell Voltage gap	String biasing
Nominal hot case	27 V	523 mA
Failure 1 cold case	55 V	436 mA
Failure 2 cold case	107 V	466 mA

As mentioned before, even in failure cases, the MTG voltage / current (string current, since blocking diodes are adopted at each string) levels are quite low if compared with threshold limits included in ECSS and literature data [1], [3], [5].

3 ESD TEST COUPONS AND TEST PLAN

The test was conducted on two ESD coupons (SN010 and SN040), fully representative of MTG front side PVA and of MTG solar panels substrate.
Coupons front side mounts two strings of three Azur Space solar cells, fully functional, 3G30 advanced type.
Coupons rear side mounts MTG representative wires and boards and additional capacitances to simulate the MTG complete string missing cells, as it is addressed in paragraph 3.1.
The two coupons are identical except for what concerns the inter-string gap:

- 0.5 mm gap (worst case manufacturing gap) on Coupon SN010
- 1mm gap (nominal gap) on Coupon SN040

SN010 coupon was planned to qualify MTG PVA, therefore to be tested at the voltage / current levels reported in Table 1; SN040 was planned to characterize the PVA limits against sustained arcs occurrences, therefore to be tested at increasing voltage and current levels: from 60V / 550mA to 110V / 2A and 123V / 1.5A. Complete lists of tests are included in the result Table 2 and Table 3.

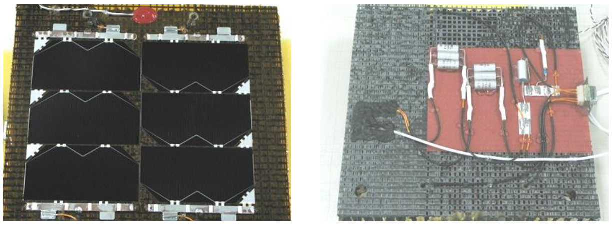

Figure 2: Testing coupon picture. Front and rear side

Higher gap coupons were also available for testing in case threshold limits for sustained arc could be reached with SN040 coupon.

3.1 String equivalent capacitances

Since the energy stored in string capacitances plays an important role during secondary arc occurrences, the missing cells of a complete flight model string (27 cells in series) are considered using an equivalent circuit that accounts for differential and common mode effects [1].

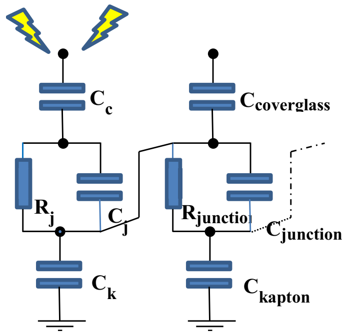

Figure 3: Equivalent circuit of two adjacent in line cells

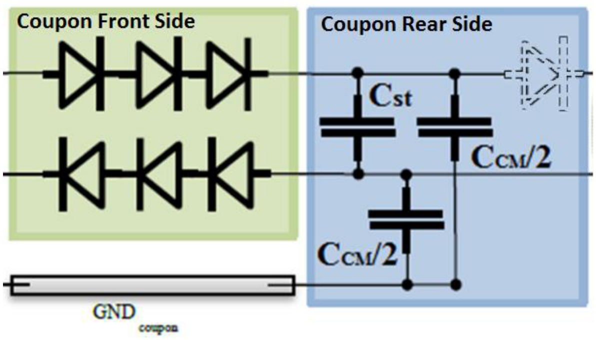

Figure 4: Equivalent capacitances circuit on testing coupon

Figure 4 shows the equivalent capacitances circuit mounted on coupons SN010 and SN040 rear side, C_{st} being the capacitance of the missing cells chain, C_{CM} being the capacitance through the Kapton for the missing cells.

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$$C_{st} = \frac{1}{2}\frac{\sqrt{C_k C_j}}{th\left(\frac{N_S}{2}\sqrt{\frac{C_k}{C_j}}\right)} = 63\text{nF} \qquad (1)$$

Where C_K is the capacitance through the Kapton of one cell as in Eq. 2 (ε_r provided by insulation layer manufacturer)

$$C_k = \frac{A}{d}\varepsilon_0\varepsilon_r \qquad (2)$$

C_J is the unction capacitance for one solar cell, as measured during MTG solar cells qualification.

$$C_{CM} = 638 \text{ nF} \qquad (3)$$

Inductive effects are already present in the test cabling wire length.

4 ESD TEST SETUP

The ESD campaign was conducted in the facility of Aerospazio Tecnologie, company highly qualified for electric propulsion and thermal-vacuum testing and for space environment simulation.

ESD test was performed at high vacuum level (pressure lower than $1\text{x}10^{-6}$ Torr), in IVG environment, generated by polarizing the coupon at -5kV and flushing it with high energy electrons generated by an electron gun. The electrons were flushed over the complete surface of the coupon through a raster and they were accelerated by the electron gun in order to reach the coupon substrate with an energy as close as possible to the coverglass secondary electrons emission peak (E_e < 1kV). The electron gun parameters (energy, focalization, current etc.) were changed by an e-gun controller while beam deflection was set using two external signal generators.

A full characterization of the plume over a surface area equal to the coupon one was performed at 80 cm from the electron gun, were the coupon was then positioned.

The coupon suspension system was reduced to the minimum, through the use of lacing chord, in order to avoid any possible interference with the test.

Figure 5 Coupon suspended in the vacuum chamber through lacing chord

The complete electrical test set up is illustrated in Figure 6.

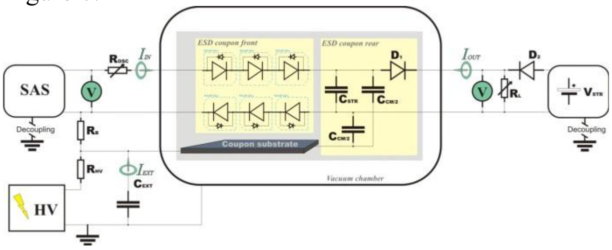

Figure 6: ESD test setup

The coupon strings are connected to a Solar Array Simulator device (SAS): one string is biased to a positive potential with respect to the conductive substrate, simulating the positive end of solar array, the other string is grounded through a resistance to the conductive substrate, simulating the negative end of solar array. Since it is of primary importance for the test to have fast transient to short circuit, the dynamic responses of SAS alone and SAS + testing cables (twisted ones) were measured though the use of a mercury switch, between 1A and 3A [1].
SAS alone showed a response of 1-2 µs, SAS + testing cable (twisted) showed a response of 4 µs; these values being similar to the illuminated solar array response and well below the duration of a typical primary discharge.

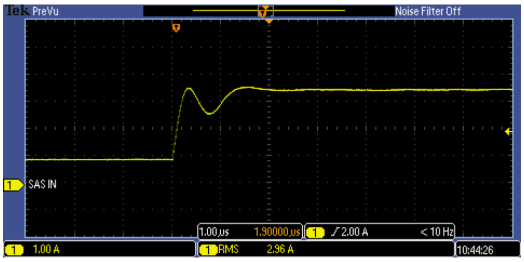

Figure 7: SAS dynamic response from 1A to 3A.

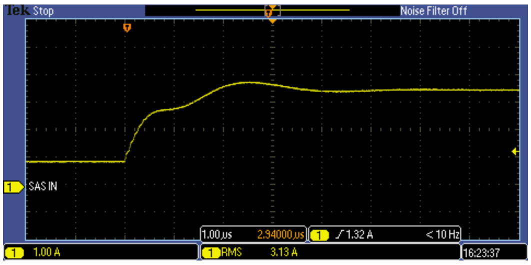

Figure 8: SAS + testing cables dynamic response from 1A to 3A

A variable resistance R_L allows the SAS to impose different voltages and currents to the strings.

An additional power supply (V_{STR} with its protection diode D_2) and an additional blocking diode D_1 allow to maintain the desired voltage gap between the two mini-strings and not to lose part of the arc current in the R_L during secondary arc occurrence, operating as in a diode switch [6]. In a secondary arc case, the voltage at the string ends drops, diode D1 is reversed and SAS makes

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its limitation current immediately available.
For Coupon SN010 testing, the SAS biased the strings at the different mission cases current (523mA for test 1, 438mA for test 2 and 446mA for test 3) and current limitation was set to values slightly higher than the biasing one. During Coupon SN040 testing, instead, the biasing current was kept constant (450mA), while the SAS current limitation was increased at each test step (550mA, 1A, 1.5A, 2A): this to protect solar cells and to limit solar cells heating [(1)].

The coupon substrate and the strings are kept at a potential of -5kV by the High Voltage power supply in the left bottom corner of Figure 6.
The capacitance in parallel to the high voltage power supply is discharged during primary discharges occurrences on the testing coupon, simulating satellite structure (blow off) and flashover discharges in space, being the first one negligible compared to the second one as already mentioned in paragraph 1.
C_{EXT} capacitance, therefore, is dimensioned in order to simulate flashover discharge, i.e. to provide the same energy stored on cover-glasses during mission. Calculation exposed in Eq. 4 provides a capacitance value in the range of 3 to 15nF.

$$\frac{1}{2} C_{EXT} V_{test}^{2} = \frac{1}{2} C_{CVG} \left(V_{CVG} - V_{SUB} \right)^{2} \qquad (4)$$

Where V_{test} = -5kV, typical values of ($V_{CVG} - V_{SUB}$) are 200V - 400V [4], C_{CVG} is the capacitance of the coverglasses of one MTG panel.
The external capacitance used for MTG test is 5nF.

The setup, showed in the picture included Figure 9, was mounted as near as possible to the vacuum chamber and the length of the wire was optimized in order to have the minimum inductance.

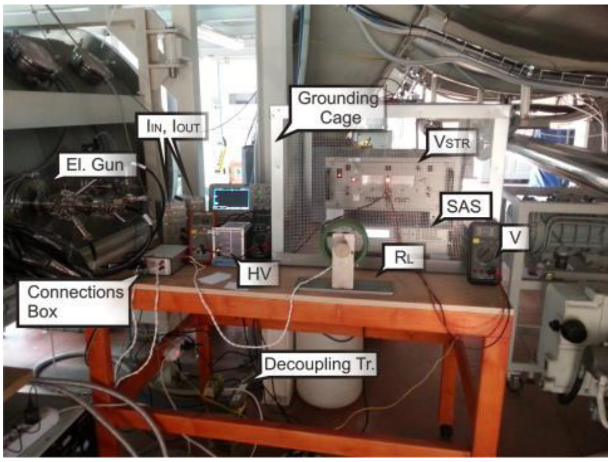


Figure 9: Set up picture

[1] The measured coupon heating with 534mA biasing was of 25°C

Discharges were recorded with a video camera positioned in front of the vacuum chamber window and discharges signals were registered by an oscilloscope connected with the three current probes indicated in green in Figure 6.

Figure 10: Recording camera

5 TEST RESULTS

The tests performed on the two coupons, together with their results are listed in Table 2 and Table 3.

For each test step, in order to have a sufficient statistics for ESD impact evaluation, at least ten primary discharges were recorded in the inter-string gap before passing to the following test step. The total number of discharges recorded for each test step was about 3 times higher, including also discharges within the same string and on coupon edges.

The IV curve of each coupon was measured before and after its ESD test campaign; after each test step of the same test campaign, the coupon functionality was checked inside the chamber through continuity and insulation test.

As already mentioned in the previous paragraphs, Coupon SN010 (with 0.5mm inter-string gap) was submitted to the MTG mission voltages and currents levels, according to the first three rows of Table 2.
None of the MTG test conditions applied to Coupon SN010 (Test 1 to 3) caused sustained secondary arcs. After test the coupon did not record any electrical performance degradation in terms of IV curve performances and PVA insulation towards the substrate.
It is however important to record that the discharges in some cases generated recombination spot on solar cells with no effect on the string electrical performance (see Figure 11).

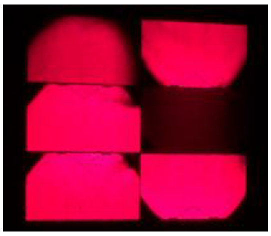
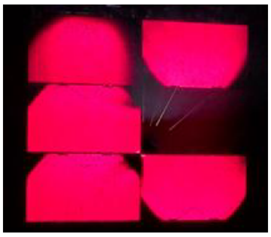
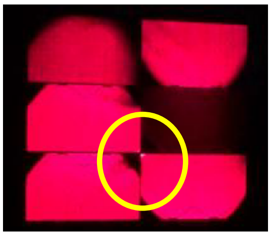
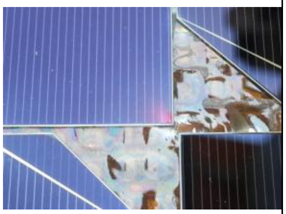
Before the discharge	Discharge image
	
Permanent recombination spot after discharge	
	

Figure 11: Recombination spot damages on solar cells

Coupon SN040 (with 1mm inter-string gap), was planned to be used for the voltage / current threshold limits determination, with the test conditions reported in Table 3. Strings biasing was kept at 450mA for the whole test phase, while the current immediately available through SAS was increased from test step 4 to 6. Since no sustained secondary arcs occurred during test 4 to 6, Coupon SN040 was also tested in a more severe environment (test 7), up to SAS limits: V=123V and I_{lim} = 1.5A.

Since also test 7 did not show the occurrence of any sustained arc, the same test conditions, were applied on Coupon SN010 (test 8 in Table 2).

Table 2: MTG ESD Qualification phase on SN010 coupon (inter-string gap = 0.5mm).

Test n°	V Gap [V]	ISAS [mA]	Test Condition MTG Reference	Results
Test 1	27	523	MTG mission Nominal case	Passed
Test 2	55	438	MTG mission Failure 1 case	Passed
Test 3	107	446	MTG mission Failure 2 case	Passed
Test 8	123	1500 (limitation)	ESD Characterization	Failed

Table 3: ESD Characterization phase on SN040 coupon (inter-string gap = 1mm)

Test n°	V Gap [V]	I_{SAS} lim [mA]	Results
Test 4	90, 110	550	Passed
Test 5	90, 110	1000	Passed
Test 6	60, 90, 110	2000	Passed
Test 7	123	1500	Passed

During Test 8, after 9 primary arcs recording on Coupon SN010 in the inter-string gap, a sustained arc occurred, determining a permanent solar cells and insulation layer damage.

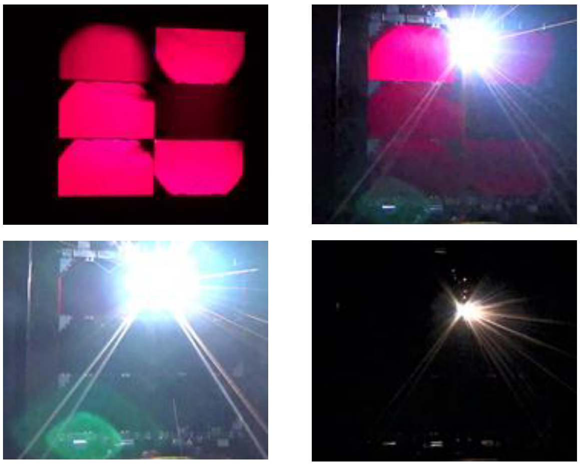
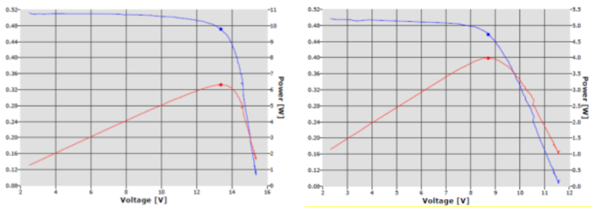


Figure 12: Sustained arc recording on Coupon SN010 (gap = 0.5mm, V=123V, I_{lim} = 1.5A)

Figure 13: Damaged coupon after sustained arc occurrence



Before ESD test 8 After ESD test 8

Figure 14: Coupon 010 IV curve before and after sustained arc occurrence

Typical discharge pictures are showed in Figure 15 and typical discharge signals are included in Figure 16 to Figure 19.

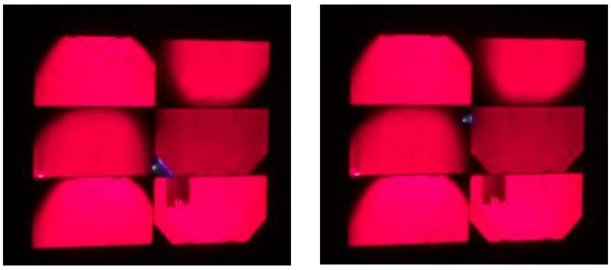


Figure 15: Typical discharges pictures (Coupon SN040)

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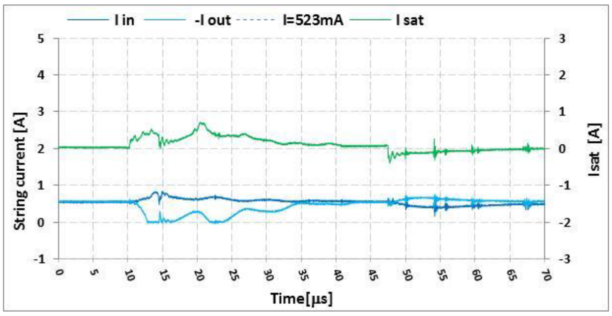

Figure 16: Typical discharge for 27V inter-strings voltage gap (523mA biasing, Coupon SN010)

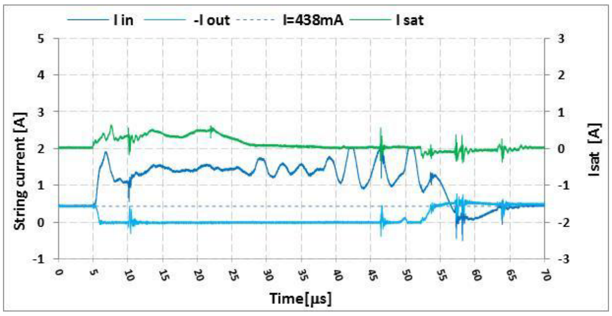

Figure 17: The strongest discharge recorded at 54V inter-strings voltage gap (438mA biasing, Coupon SN010)

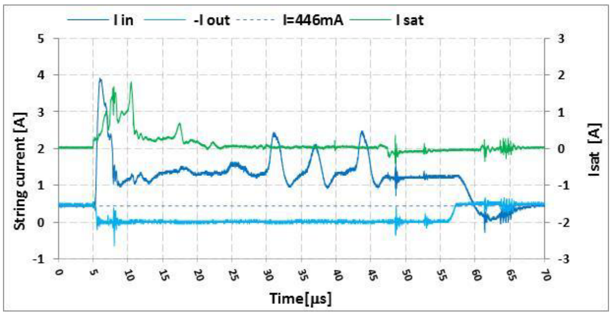

Figure 18: Typical discharge signal at 107V inter-string gap (446mA biasing, Coupon SN010)

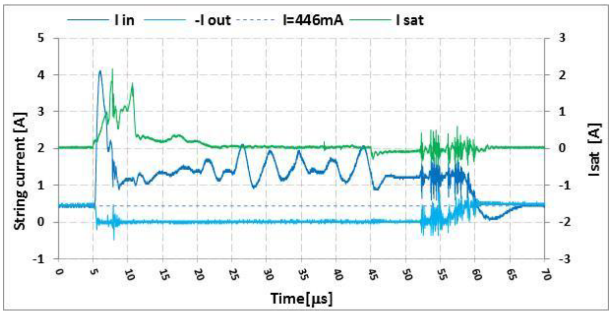

Figure 19: Typical discharge signal at 123V inter-string voltage gap (446mA biasing, SAS current limitation at 1.5A, Coupon SN010)

6 CONCLUSIONS AND FURTHER DEVELOPMENTS

The here presented test campaign showed MTG panel design (0.5 mm gap as a very worst case) to have wide voltage and current margins to the threshold limits for sustained arcs occurrences: 107V / 446mA against a limit of 123V / 1.5A.

The campaign was also a great chance for Leonardo Company and Aerospazio Tecnologie to develop competences in ESD testing on PVA.
That said, some test aspects could be addressed only partially and are worthy further investigations:

- Coupon temperature role (during present test the coupon temperature at different coupon biasing, was indirectly measured before and after each test step)
- The effects of electron beam current density and impact spot on the coupon
- The effect of testing time (electron flushing) on discharge rate.
- The discharges direction along the strings and in the inter-string gaps

The test setup itself has room for improvement for what concerns the discharges recording system (that shall be triggered to the discharges signals at the oscilloscope), the coupon surface voltage recorder (not available at this stage) and the instruments power limitations (maximum reached 123V / 1.5A).
Finally, the results here exposed shall be integrated with a more extended test campaign including higher voltages and string biasing levels and a wider set of inter-string gaps in order to have a more exhausting characterization of the limits for permanent damages occurrences on PVA due to ESD phenomena.

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