ELECTROSTATIC DISCHARGES ON A 1m² SOLAR ARRAY COUPON – INFLUENCE OF THE ENERGY STORED ON COVERGLASS ON FLASHOVER CURRENT.

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ABSTRACT:
Experiments simulating charging on a geostationary orbit were done in laboratory on a large solar array coupon (592 x 1333 mm) in order to characterize electrostatic discharges. Such discharges were triggered by inverted voltage gradient situation produced on the coupon biased at -5000V by using an electron beam striking the sample. Current probes monitored blow-off and flashover currents produced by electrostatic discharges and showed that almost all the energy stored on the cover-glasses can participate to the flashover discharge. Surface potential measurements performed before and after electrostatic discharges, show neutralization area where the differential voltage between the cover glass surface and the coupon decreased from +1000V to +200V. The size of the neutralization zone varied with the discharges: while some discharges produce neutralization on a limited surface, other can produce neutralization all over the coupon.

1. INTRODUCTION

Satellites on a geostationary orbit interact with the space environment: while the satellite body is negatively charged up to several kilovolts, dielectrics build up a differential charge as high as 1000V. The differential voltage created is called inverted voltage gradient situation and can trigger electrostatic discharges (ESD). On solar arrays, such discharges can degenerate in some cases into destructive secondary arcs between adjacent cells. Since power losses have been produced by such phenomena, realistic ground tests of ESD and secondary arcs on solar arrays are a main concern. In this paper we present experiments made on a large solar array coupon as part of a CNES study performed at ONERA in order to set a European standard in ground tests (ECSS E20-06). This work is associated with a Japanese study and aims to set the basis of an ISO standard for ESD and secondary arcs. This study aimed to characterize electrostatic discharges on a large solar array coupon: ESD are characterized by a blow-off discharge and a flashover discharge. The blow-off discharge represents electrons emitted from the satellite (for example metallic interconnects on solar arrays) to the space environment. Electrons participating to the blow-off are charges accumulated by the satellite body. The flashover discharge represents electrons emitted from the discharge location to another part of the satellite (for example other cover-glasses in the case of ESD on solar arrays). Electrons participating to the flashover come from differential charges accumulated by dielectrics. Usually, electrostatic discharges tests are performed on small samples (from 2 to 12 or 16 solar cells) and the blow-off discharge is simulated by adding a capacitance which value represents the charges accumulated by the satellite (around 300pF for a geostationary satellite). However, depending on the experiments, flashover currents are not simulated or are simulated by adding another capacitance which value represents a certain amount of cover-glasses supposed to participate to the discharge. Since both cases don't simulate the real case (not enough charges in the first case, capacitance discharges give wrong waveform), experiments on solar array coupon as large as possible were decided to determine the correct amount of charges and the way they are dissipated (i.e. peak current, discharge duration, waveforms...).

2. EXPERIMENTAL SET-UP

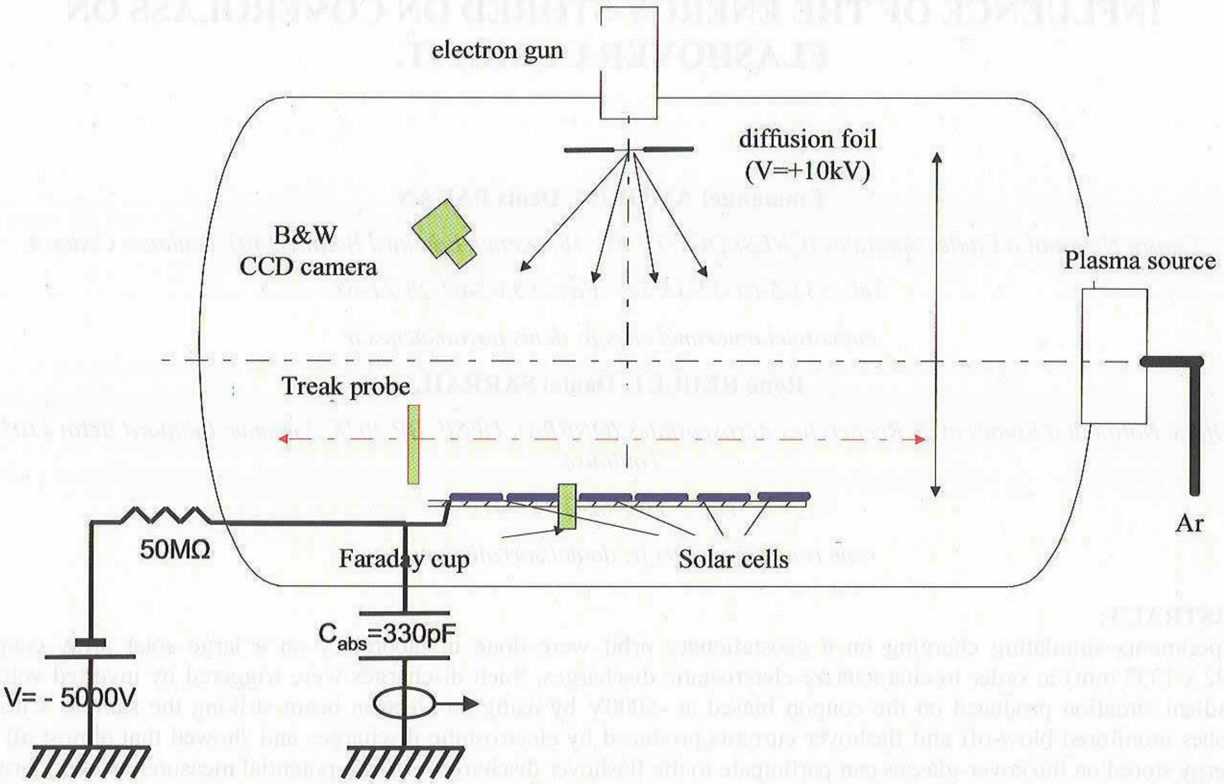


Figure 1: Experimental set-up: schematic view. The sample is put in vacuum and biased to -5kV and irradiated by an electron beam. Probes monitor currents during ESD and a non-contacting potential probe performed surface potential distribution. The plasma source was used after each discharge to reset the differential voltage.

Laboratory experiments were developed to simulate electrostatic discharges on a large solar array coupon. The tests were carried out in a stainless steel vacuum chamber 1.85m in diameter and 3m in length, evacuated to a residual pressure of 10^{-8}hPa during the experiments.
Solar cells made of silicon, are placed above a Kapton® film in real satellite geometry. This Kapton® film insulates the cells from the structure of the satellite, which acts as local ground. A cover glass protects each cell from heavy particle bombardment (ions, micro meteors). Cells are joined by metallic interconnects made of silver in order to obtain the required operating current and voltage. The solar array coupon used in this study was provided by Sharp Corporation and Alcatel Space Industry. All the materials used in the sample construction are the same as the materials used on satellites. Photographs of the solar array coupons used in the experiments are shown in Figure 3. The size of the coupon is 1330×590mm², and the size of each solar cell is 70×35mm². The coupon is made of 19 strings of 16 silicon cells, and contains 304 cells.

The experimental set-up shown in Figure 1 was made in order to simulate electrostatic discharge occurring on solar arrays of a geostationary satellite. The coupon was biased negatively at –5000 volts by a low current power supply through a 50MΩ. In order to simulate the blow-off discharge, capacitor C_{abs} used to represent the charges accumulated by the satellite was placed in vacuum. During our experiments, C_{abs} values were 330pF: this value represents the absolute capacitance of a geostationary satellite structure with respect to space plasma. In real operation the satellite current and voltage values are determined by the arrays of solar cells. A solar array consists of parallel groups of cells each composed of solar cells wired in series. In our case, since we wanted to characterize only the blow-off and the flashover discharges, we didn't bias the strings one respect to another. The electrical circuit was set to minimize parasite inductance due to the length of the wires between the samples in vacuum and the power supply outside the vacuum chamber.

The method chosen to produce the inverted gradient voltage situation uses an electron beam. The coupon was biased at –5000V and an electron beam having a mean energy of 5,3keV irradiates the coupon surface. The electron gun produces a focalized electron beam that is diffused by a metallic foil. In the beginning, when the sample potential is -5000V, the electrons strike the samples with a very low incident energy ranging from tens to hundreds of electron-volts, and lead to secondary electron emission from the cover-glasses. Furthermore, at this energy level the secondary emission coefficient has a value larger than one: the cover-glass potential become more positive than the substrate potential maintained at –5000V by the power supply. The cover-glass potential reaches a maximum value (around -4000V) after few minutes. Thus, the cover glass is less negative (-4000V) than the rest of the sample (-5000V) defining in this way the "inverted voltage gradient situation". This high potential gradient situation leads to electrostatic discharges (ESD). Figure 7 and Figure 8 show the maximum differential voltage obtained on X and Y axis after 12mn of irradiation by the electron beam: while the coupon and silver interconnects are at -5000V, the top of the solar cells, i.e. the cover-glasses are at -4000V. One can see variations depending on the strings (X-axis) due to the non uniformity of the beam for such a large distance (around 1.4m), while the differential voltage is nearly constant on the Y-axis.

In our experiments these electrostatic discharges occurred on the metallic interconnects or at the solar cell edges. The electrostatic discharges are characterized by a blow-off current and a flashover current. Rogowski coil current sensors (Pearson, 300Hz to 200MHz bandwidth) were used to monitor the discharge of capacitor C_{abs}, corresponding to blow-off discharges to chamber ground when ESD occurs and the current flowing through the strings. During these experiments, wires + and - of each strings were connected and measured by the current probes. Dedicated current probes monitored the current flowing through strings n°9, 10, 11, 12 and 13 while another current probe monitored the current flowing through the other strings (i.e. strings n°1-8 and 14-19).

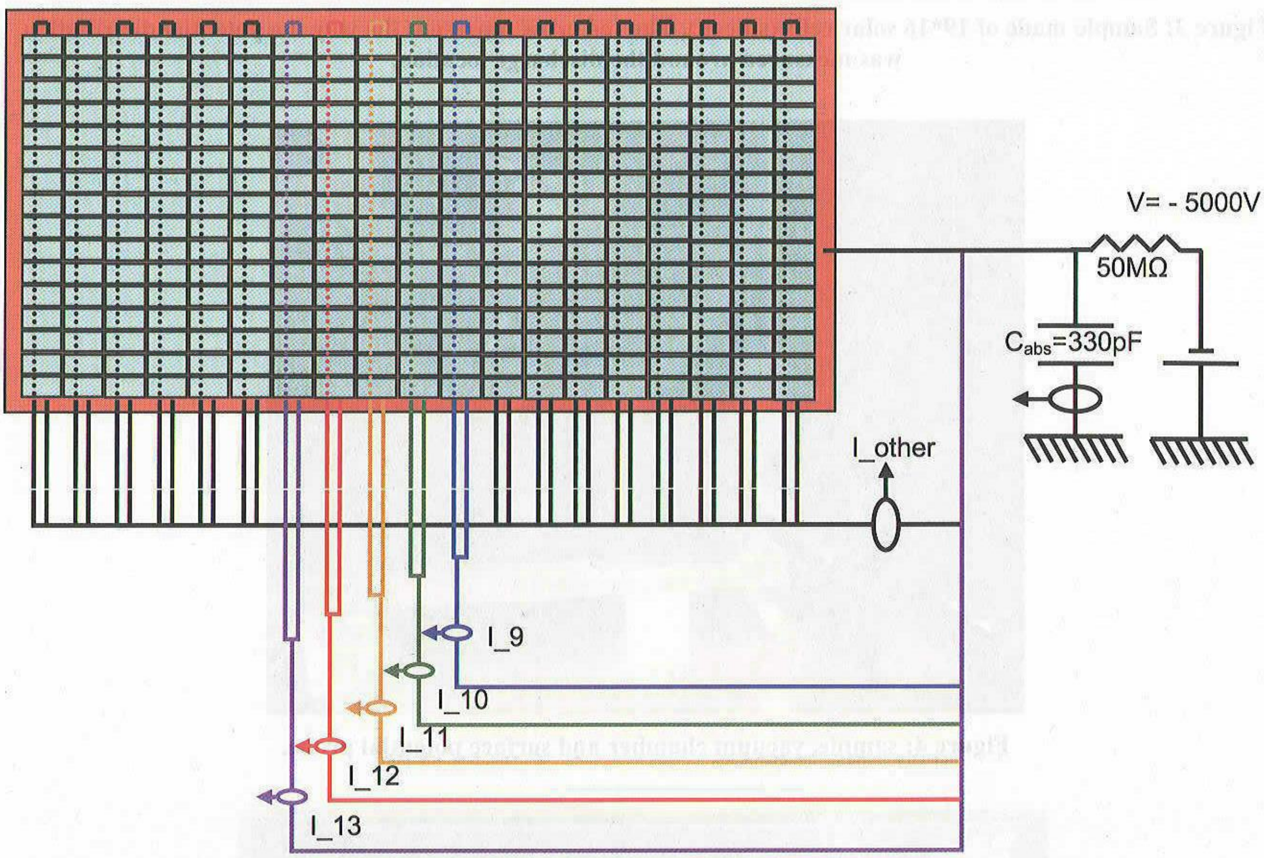


Figure 2: Current measurements schematic view: current passing through strings 9 to 13 are monitored using current probes. Both wires of each string are connected together and measured by the same current probe. Wires of all the other strings are also connected the same way and measured by another current probe (I_other). The blow-off current was also measured by monitoring the 330pf capacitor discharge.

The surface potential before and after discharge was also monitored using a non-contacting surface potential probe. Once the discharge location was precisely identified, the surface potential was monitored on one line and one column (i.e. one string) around the discharge point as shown in Figure 3. When an ESD was triggered and the surface potential measured, we used an Argon plasma source to neutralize completely the coupon, in order to have almost the same potential distribution over the sample before each discharge.

A high voltage probe measured also the coupon voltage during electrostatic discharges and a black and white CCD camera was used to film the sample in the vacuum chamber. This method allowed us to localize the position of the discharges on the solar array coupon.

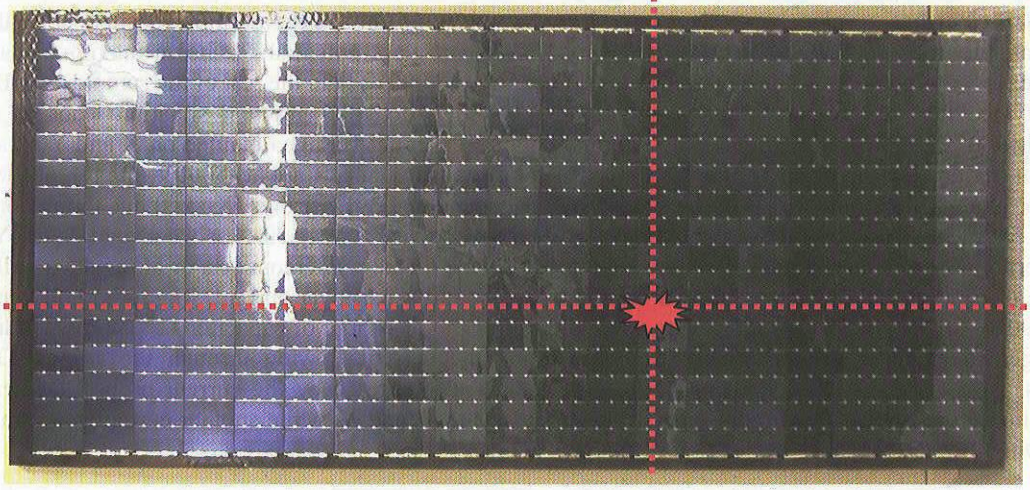


Figure 3: Sample made of 19*16 solar cells (silicon). The red cross represent the way the potential distribution was measured around the discharge location.

Figure 4: sample, vacuum chamber and surface potential probe.

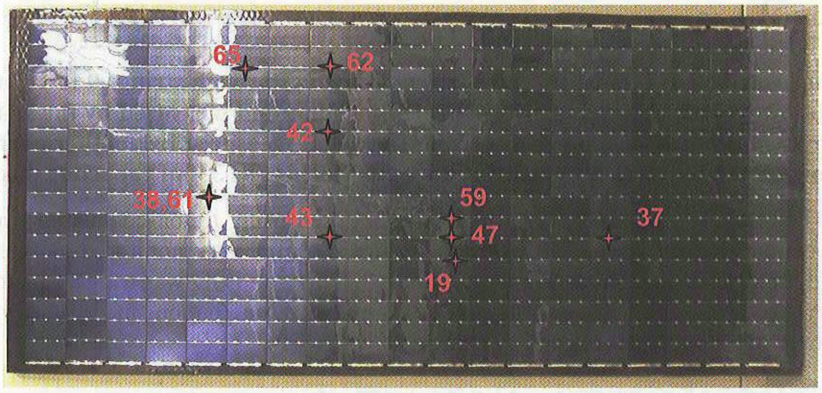


Figure 5: discharge locations: discharges described in this paper.

3. RESULTS

More than 100 electrostatic discharges were obtained on this solar array coupon. From these tests, flashover discharges were characterized. Figure 6 shows where some electrostatic discharges occurred. One can see that discharges where triggered almost everywhere on the coupon. There is no clear correlation between the discharge lifetimes and their location but it seems that discharges lasting more than 65µs tend to be preferably located on the middle of the sample.

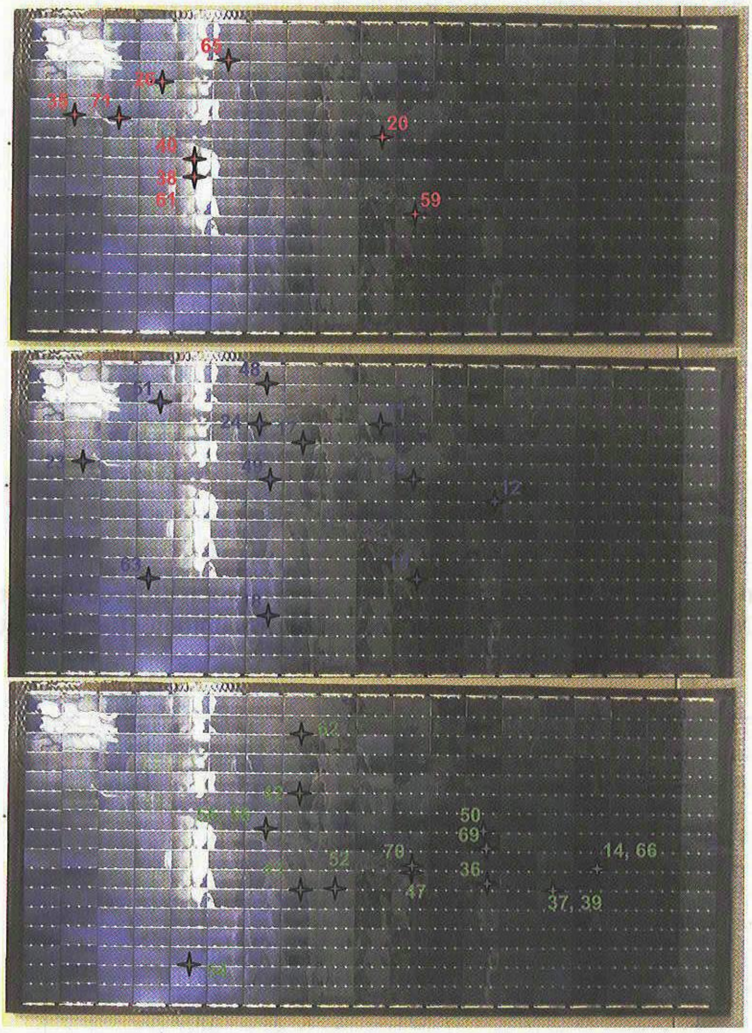


Figure 6: Discharge location versus discharge lifetime.

3.1. POTENTIAL DISTRIBUTION

Figure 7 to Figure 11 show potential distribution before and after electrostatic discharges. One can see that the neutralized area size and the differential voltage values depend on the discharge: location, lifetime and dissipated charges (see also 3.2). However, we can say that all the differential voltages between the solar cells and the coupon are reduced after each ESD. The maximum differential potential reduction triggered by electrostatic discharges depends on the discharge and ranged from 500 to 800V. The neutralization area can be divided into two zones: the first one where the differential voltage reduction is maximum (i.e. absolute cover-glass potential is -4000V before the discharge and around -4600V after the discharge), and the second one where the differential voltage reduction is less than 500V (i.e. absolute cover-glass potential after the discharge is between -4100 and -4500V). The first zone has a size depending on the discharges: some discharges produced a maximum neutralization all over the coupon (1300x590 mm²) while other produced a maximum neutralization over a limited area (400x200 mm² for discharge 65, see Figure 10). The area not covered by this first zone defines the second zone or "partial neutralization zone".

On Figure 7, Figure 8, Figure 9 and Figure 10, one can see that discharges having almost the same lifetime (less than 50µs for discharges 19, 61 and 65, around 100µs for discharges 37, 42, 43, 47 and 62) can produce different neutralization (size and differential potential reduction). However discharges having a higher lifetime tend to produce a "better" neutralization (Figure 11).

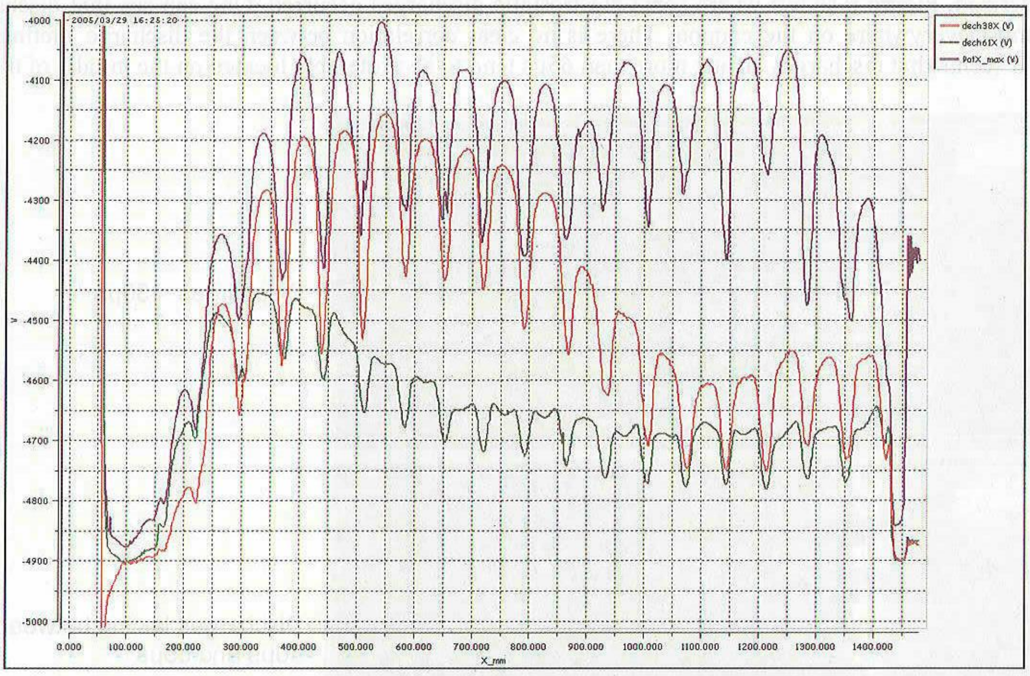


Figure 7: surface potential distribution on the X-axis. PotX_max shows the maximum differential voltage obtained after 12mn of irradiation. Dech38X and dech61X show the potential distribution after respectively discharge n°38 and 61.

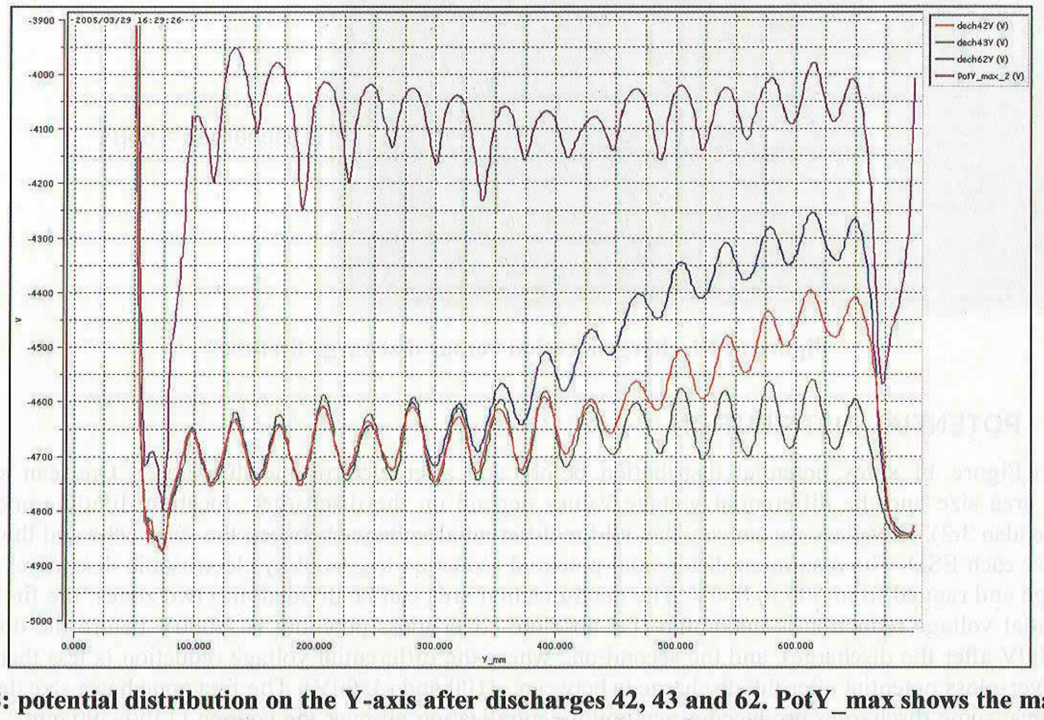


Figure 8: potential distribution on the Y-axis after discharges 42, 43 and 62. PotY_max shows the maximum differential voltage obtained after 12mn of irradiation.

discharge	Lifetime (µs)
19	51
37	98
42	105
43	100
47	106
61	44
62	103
65	30

Table 1: discharge lifetime (discharges described in section 3.1 and 3.2)

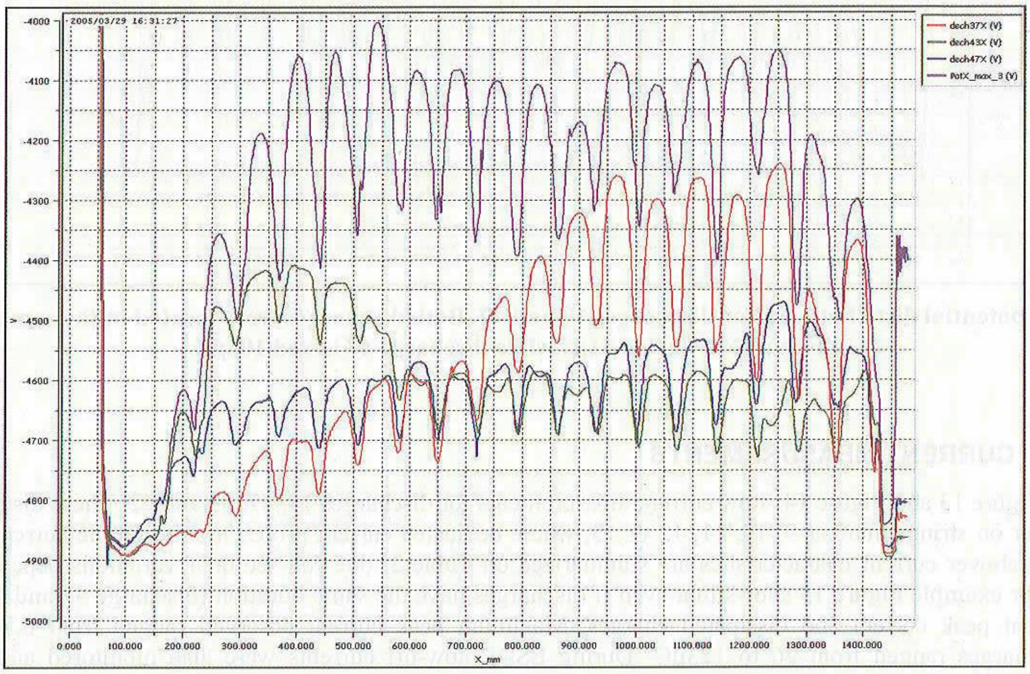
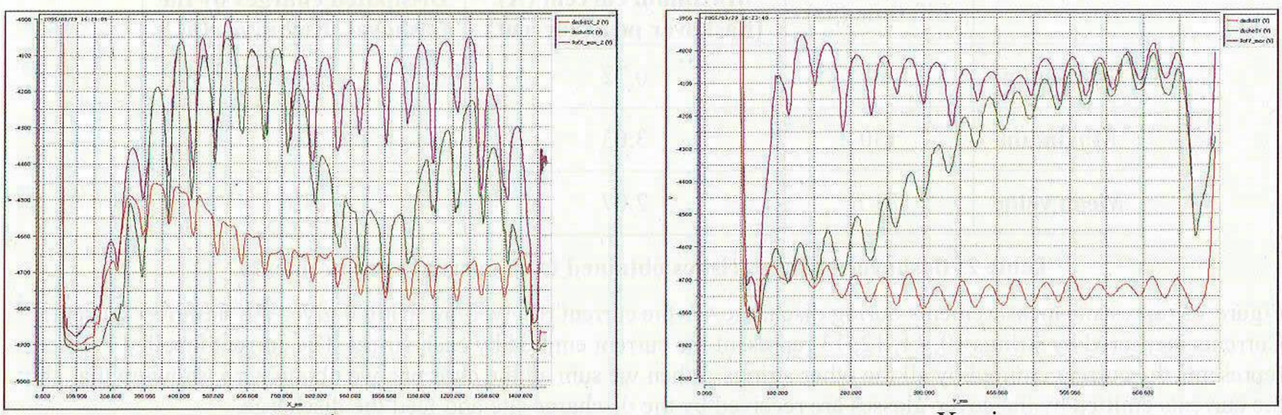


Figure 9: potential distribution on the X-axis after discharges 37, 43 and 47.



X-axis Y-axis

Figure 10: potential distribution after discharges 61 (red) and 65 (green). Discharge 65 produced a limited neutralized area (400x200 mm²).

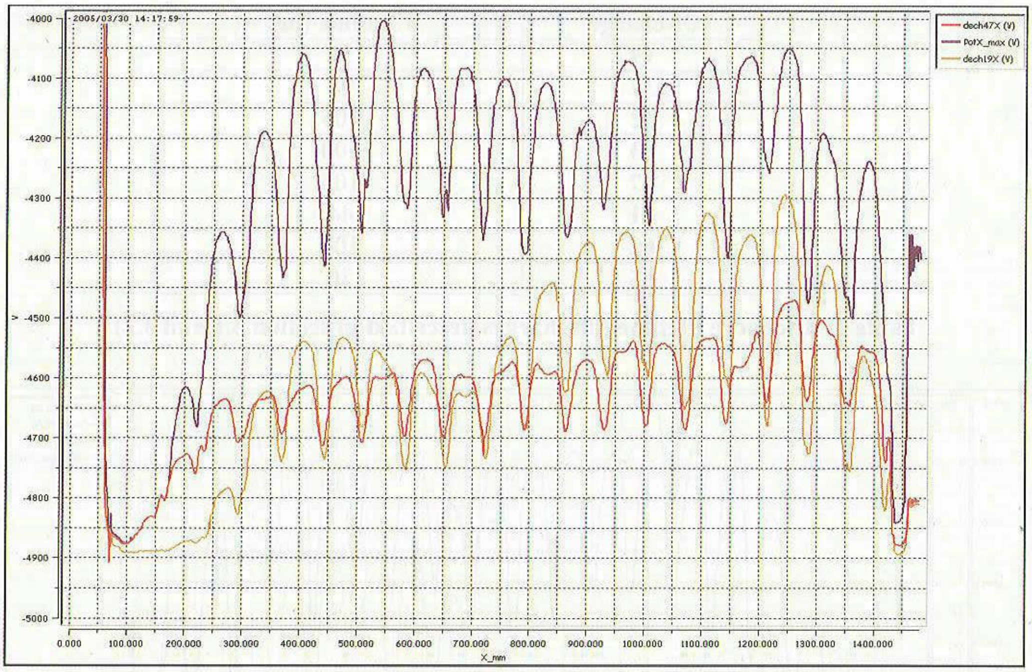


Figure 11: potential distribution after discharges 19 and 47. Both discharges were located in the same place, but discharge 19 lasted 51μs while discharge 47 lasted 106μs.

3.2. CURRENT MEASUREMENTS

Figure 12, Figure 13 and Figure 14 show current measurements for discharges 19, 47, 53 and 62. These discharges were located either on strings number 9, 10, 11, 12 or 13, where dedicated current probes monitored the current emitted or received. Flashover current characteristics are summarized on Table 2: one can see their variations depending on the discharge: for example Figure 13 shows that even if discharges have the same duration (discharge 47 and 62) they can have different peak current and dissipated charges. Maximum peak current observed ranged from 0.7 to 3A and dissipated charges ranged from 26 to 123μC. During ESD, blow-off currents were also monitored and the 330pF capacitor was always completely discharged.

	Lifetime (μs)	Maximum current (A) (flashover peak current)	Dissipated charges by the flashover discharges (μC)
Minimum	10	0.72	26
Maximum	130	3.03	123
Mean value	70.7	2.07	81.6

Table 2: flashover characteristics obtained from current measurements.

Figure 12 represents measurements during discharge 47: the current received by string 9 gives the flashover current. Currents measured by strings 10, 11, 12, 13 represent the current emitted by each string. The current labelled I_other represents the current emitted by all the other strings. When we sum all the currents, we obtain zero, showing that all the currents emitted by the cover-glasses are received by the discharge site and feed the discharge.

On Figure 12 and Figure 14 current emitted by the strings where the discharge didn't occur are shown (strings 10, 11, 12, 13 for discharge 47 for example). These currents represent the neutralization current emitted by this strings during the flashover discharge.

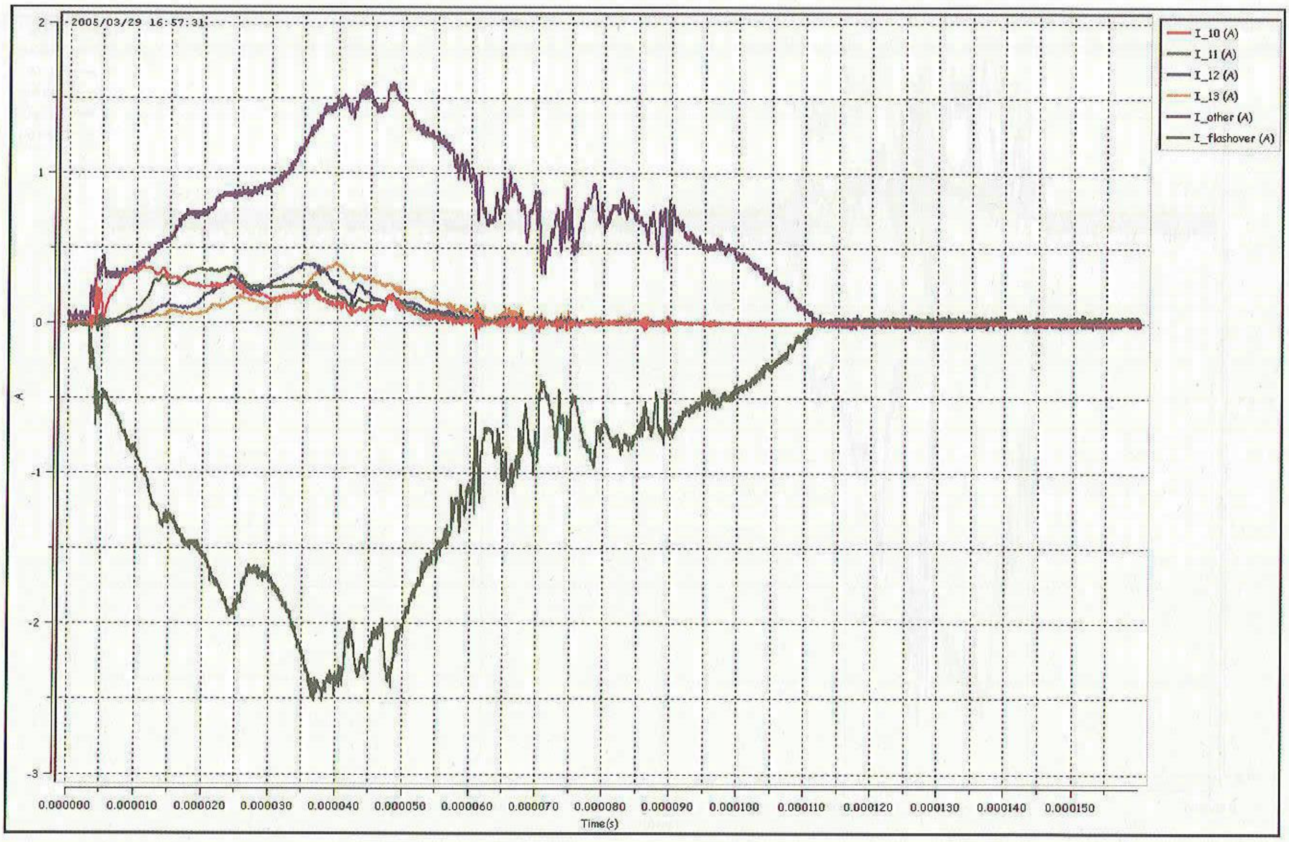


Figure 12: Current measurements obtained on discharge 47. The discharge was located on string n°9: I_9 gives the flashover current while I_10 to I_13 give the current emitted from the strings n°10-13. I_other shows the current emitted from all the other strings.

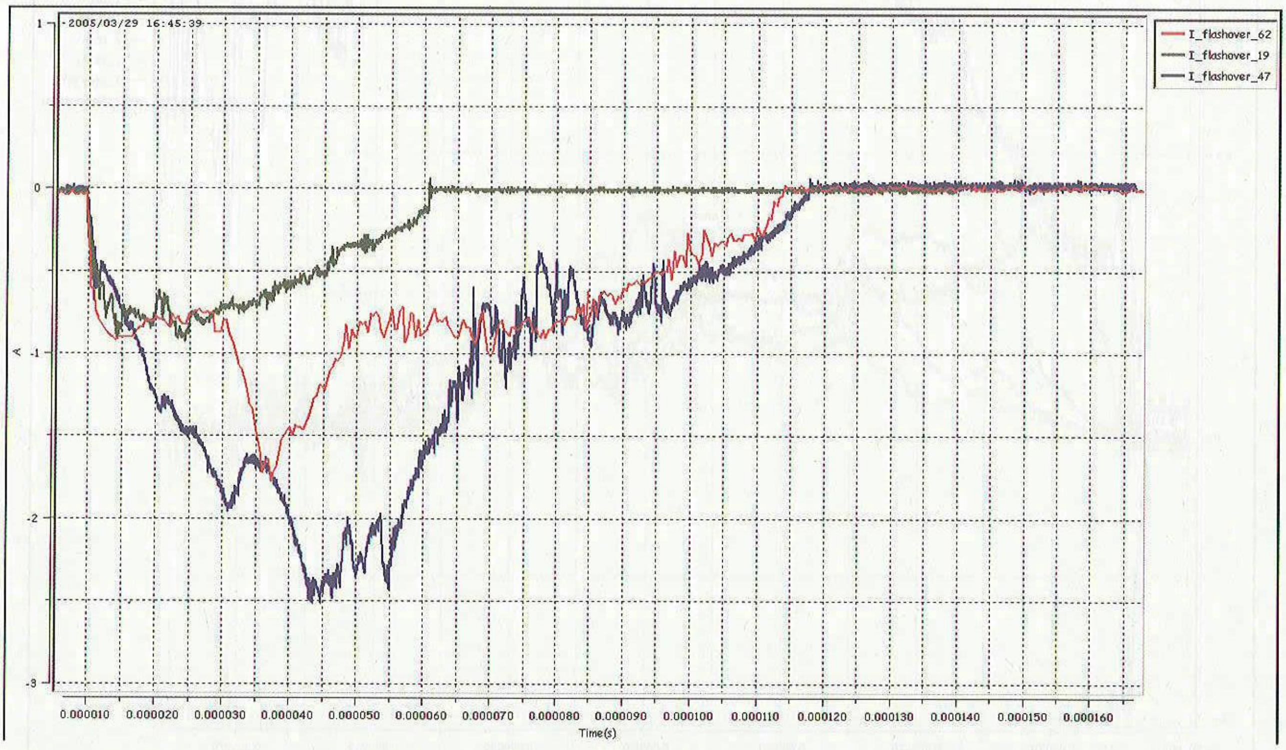


Figure 13: flashover currents. Discharges 19 and 47 are on the same location, discharges 47 and 62 have same duration but peak current and dissipated charges are different.

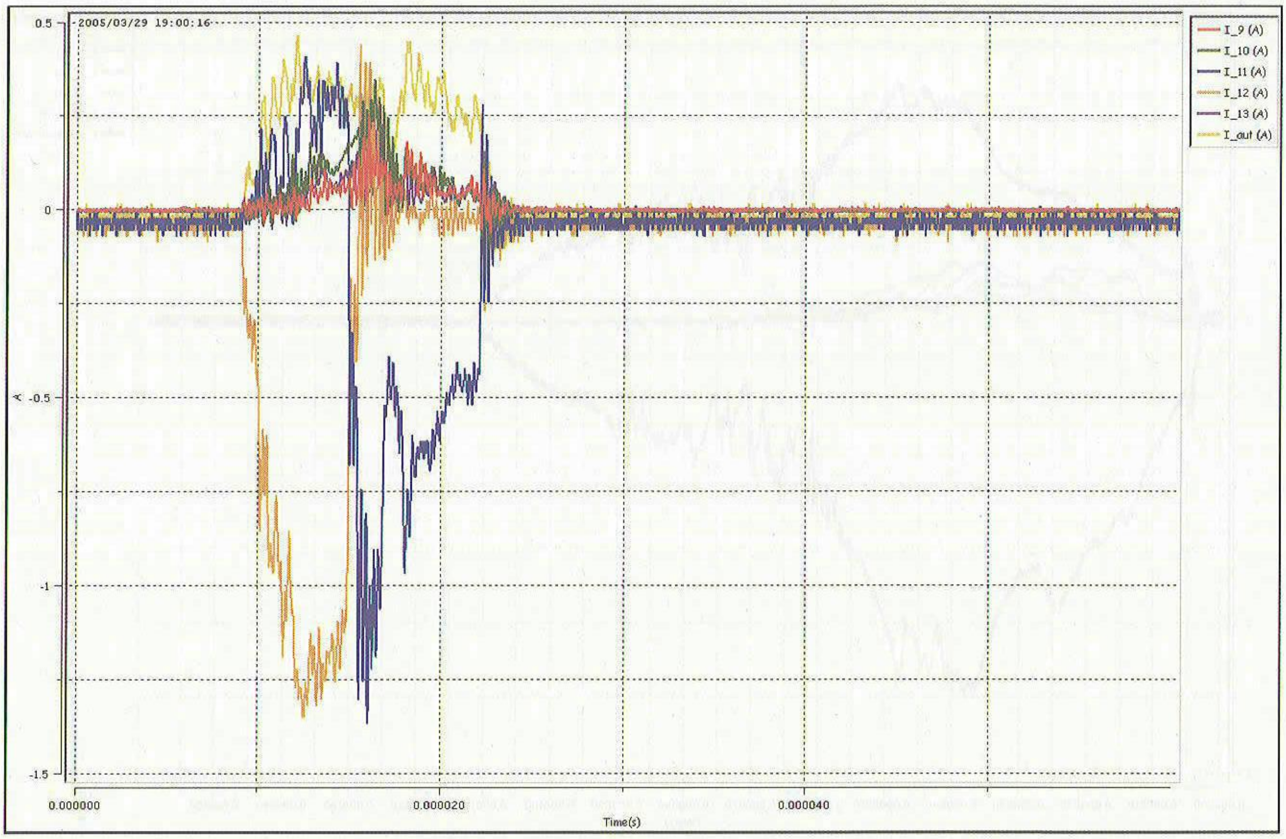


Figure 14: discharge 53: the only case of flashover current seen on different strings. Here the flashover current is received first by string 12, then by string 11 showing the discharge location has moved.

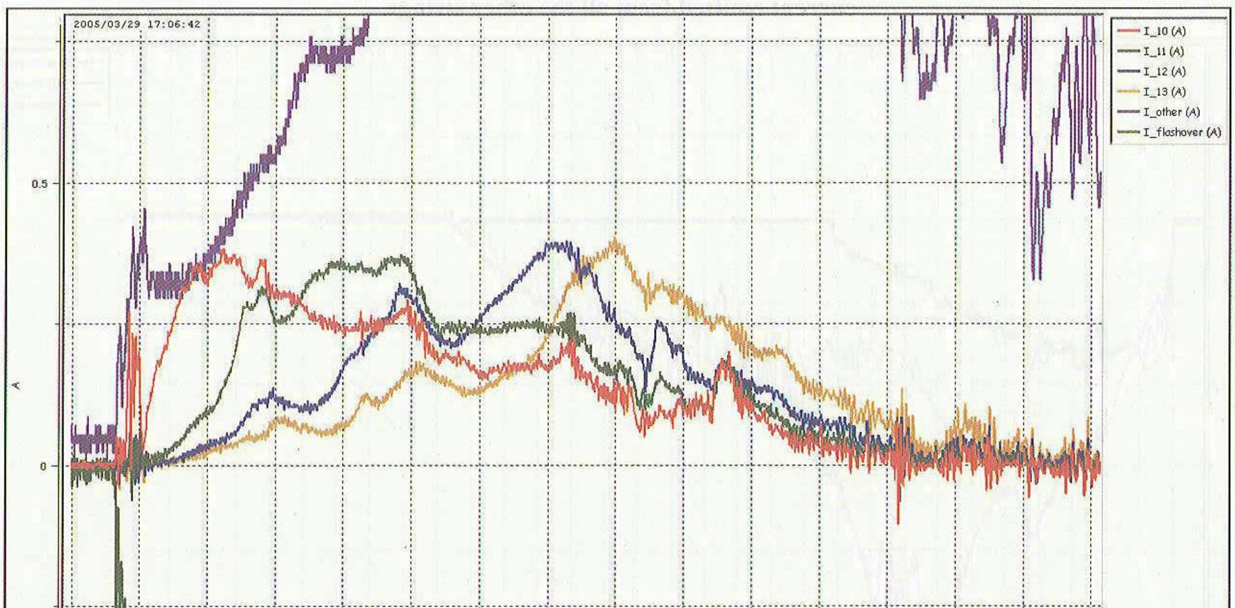


Figure 15: current emitted by strings n°10-13 during discharge 47. Plasma propagation speed was calculated using peak currents and give value from 0.7 to 1.1 10^{+4}m.s^{-1}.

4. DISCUSSION:

The neutralization area size and the flashover currents measured during electrostatic discharges depend on discharge characteristics: no clear law using the discharge location or discharge duration can explain this variability since same locations or same durations can produce very different results. However statistics on these measurements allow us to characterize flashover discharges occurring on a $1m^2$ solar array coupon: current measurements and video observations show that each electrostatic discharge is located in one place, except few exceptions (see Figure 14) and if many discharges produce neutralization over a limited area, about 15% have neutralized the entire coupon surface.

We can characterize flashover discharges by their dissipated charges: these charges are believed to be directly correlated with charges stored on the cover-glasses glued on the top of the solar cells. For the cover-glass capacitance calculation, we have to consider the thickness of the cover-glass and the glue thickness between the cover-glass and the cell. For a dielectric surface S we have:

$$C_{cg} = \varepsilon_0 \varepsilon_r \frac{S}{d}$$

Where ε_r is the relative permittivity and d is the thickness of the dielectric (here ε_r and d referred to both the cover-glass and the glue). For $\varepsilon_r = 3.5$ and d = 140μm (100μm for the cover-glass and 40μm for the glue) we obtain:

$$C_{cg} = 223\ nF / m^2$$

Potential distributions after ESD show that the neutralization area can have a minimum size of 400x200 mm^2, and the maximum size is when the neutralization was all over the coupon, i.e. all the cells (304 solar cells): the neutralized area was between $0.1m^2$ and $0.75m^2$. Using the calculated C_{cg} ($223nF/m^2$), the cover-glass capacitance ranged from 23 to 170nF depending on the area. If we take 800V as a mean value of the differential potential reduction, the dissipated charges range from 19 to 136μC. These values are in good agreement with the dissipated charges calculated from the flashover current measurements which varied between 26 and 123μC and show the strong correlation between the charges stored by the cover-glasses and the flashover current.

From the current measurements made on strings close to the discharge location (for example strings 10, 11, 12, 13 on discharge 47, see Figure 12) we can estimate how the charges stored on the strings are neutralized by the flashover current. If we calculate the propagation speed of the flashover using the peak current, we obtained speed ranging from 0.7 to 1.2 10^{+4} m/s (mean value: 0.77 10^{+4} m/s), depending on the discharge. These values are clearly in the same order of magnitude than plasma expansion speed in vacuum and one can say that the neutralization around the discharge location is due to plasma propagation. However if we look at the first microseconds of the current measurements, one can see the neutralization begins immediately, i.e. current is emitted at the beginning of the discharge, even for strings separated from the discharge by more than 20cm: this cannot be assumed by plasma propagation. Thus, we should consider also electron neutralization to explain neutralization by flashover discharges.
In order to confirm this hypothesis, we have made plasma expansion calculations. For discharge 47, we calculated the perimeter evolution of the plasma bubble generated at the discharge location. We supposed that the propagation speed was v_{plasma} = 0.77 10^{+4} m/s (mean value of flashover propagation). Thus the plasma bubble radius is defined by $r(t) = v_{plasma} . t$ and the bubble perimeter is determined by the intersection between the circle defined by r(t) and the coupon dimensions. A perimeter calculation for a discharge having the same location as discharge 47 is shown on Figure 16. Then we calculated the current provided by the plasma neutralization using:

$$I = \frac{dQ}{dt} \qquad \text{And} \qquad Q = C.\Delta V = \varepsilon_0 \varepsilon_r \frac{S}{d}.\Delta V$$

Where ΔV=800V, so

$$\frac{dQ}{dt} = \varepsilon_0 \varepsilon_r \frac{\Delta V}{d}.\frac{dS}{dt}$$

In our case, we assume the neutralized area at each time step dt is:

$$dS = perimeter.v_{plasma}.dt$$

Where "perimeter" is the plasma bubble perimeter.
Thus:

$$I = perimeter.v_{plasma}.\varepsilon_0 \varepsilon_r \frac{\Delta V}{d}.$$

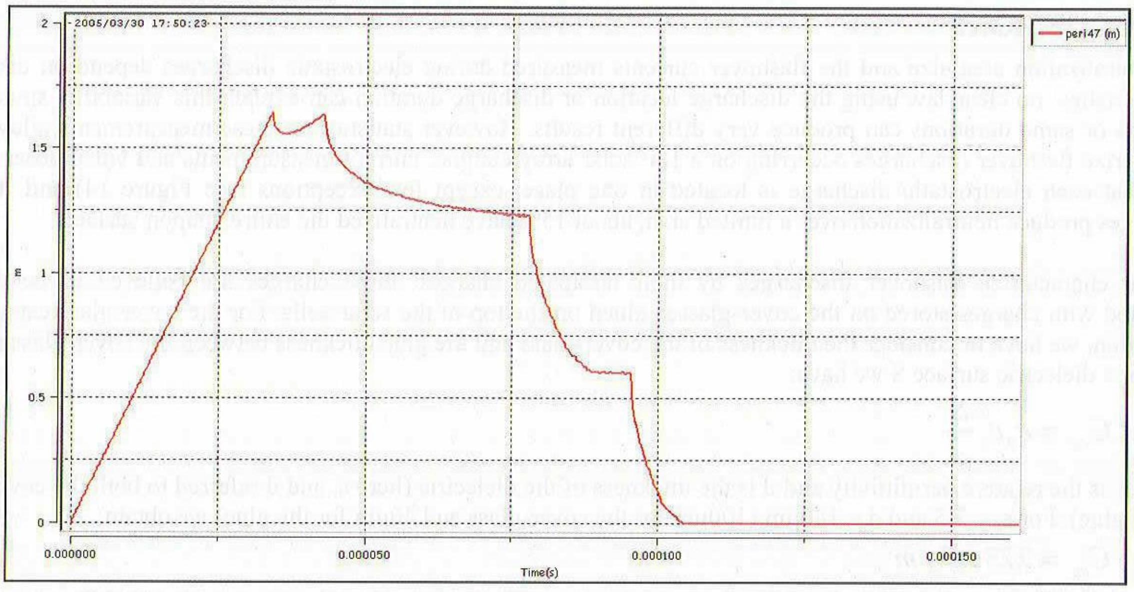


Figure 16: perimeter calculation. From the same location than the discharge 47, and using 0.77 10^{+4} m/s as the propagation speed, we calculated the perimeter evolution with time of a plasma bubble created at the discharge location.

From the perimeter shown on Figure 16, we obtained the current shown on Figure 17. This figure shows the comparison with the flashover current measured during discharge 47: one can see good agreement in terms of duration and dissipated charges (123 and 125µC) but peak current and rise time are different. Differences between the current measurement and the current calculation in the first microseconds show that plasma propagation cannot explain by itself the neutralization, and that electron neutralization has to be considered.

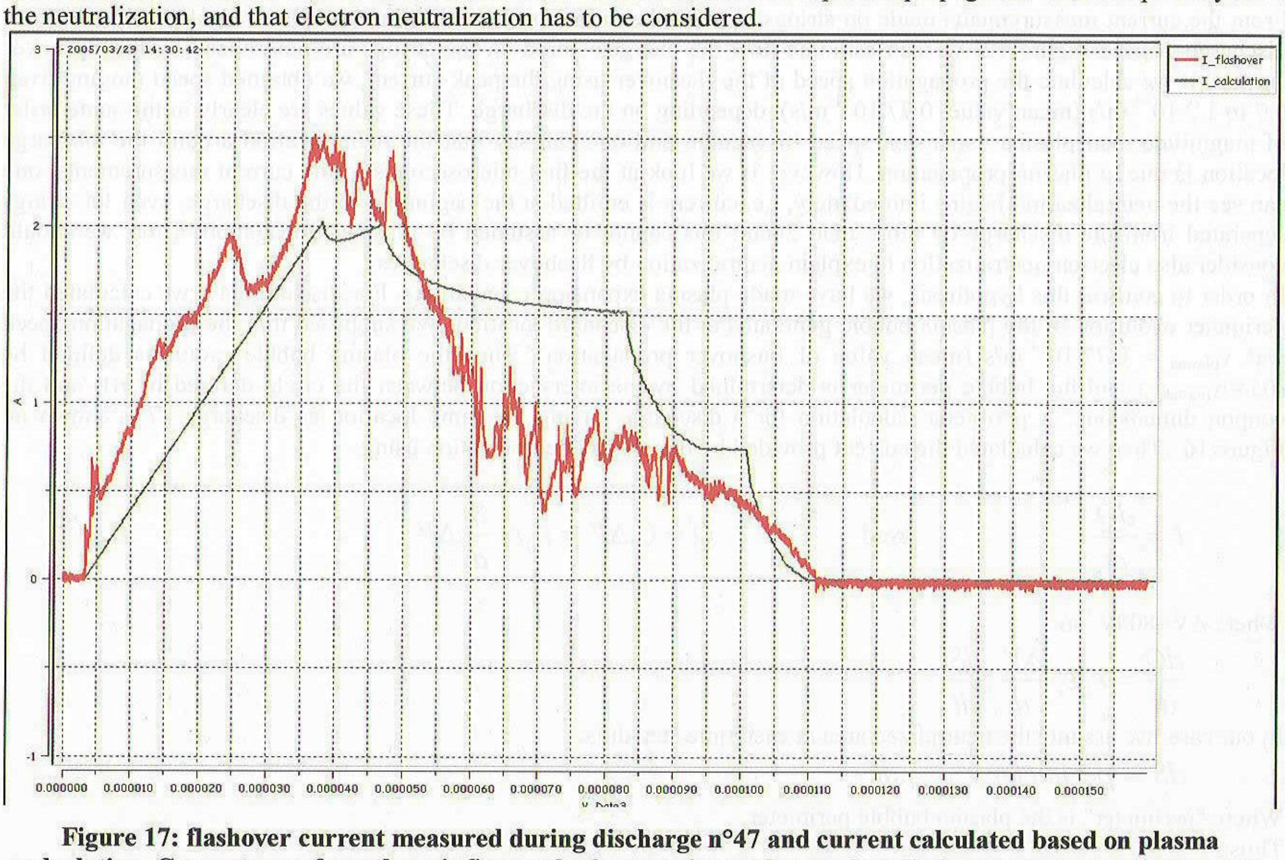


Figure 17: flashover current measured during discharge n°47 and current calculated based on plasma calculation. Current waveform doesn't fit exactly the experimental curve but dissipated charges are the same: 125µC.

However, since the perimeter calculation gives a good general agreement, calculations have been done to evaluate plasma bubble expansion on a typical solar panel of a geostationary satellite. We assumed a complete neutralization of the solar panel, calculated the perimeter evolution on a 3x4 m² panel and calculated the flashover current we should expect using the same capacitance and differential voltage values as for the discharge 47. Figure 18 show an example of this kind of calculation. Peak current is around 6A, the discharge duration is around 520μs, and dissipated charges are around 1.92mC. From the comparison between measurements and calculations shown on Figure 17, we can expect that the real flashover current in the case of a 3x4 m² panel would have different rise-time and higher peak current than the one calculated. On Figure 18 we show a suggested flashover current simulation for solar array tests: peak current of 6.5A and 600μs duration give amount of charges of 1.95mC which is in good agreement with the perimeter calculation (see also ref[1].

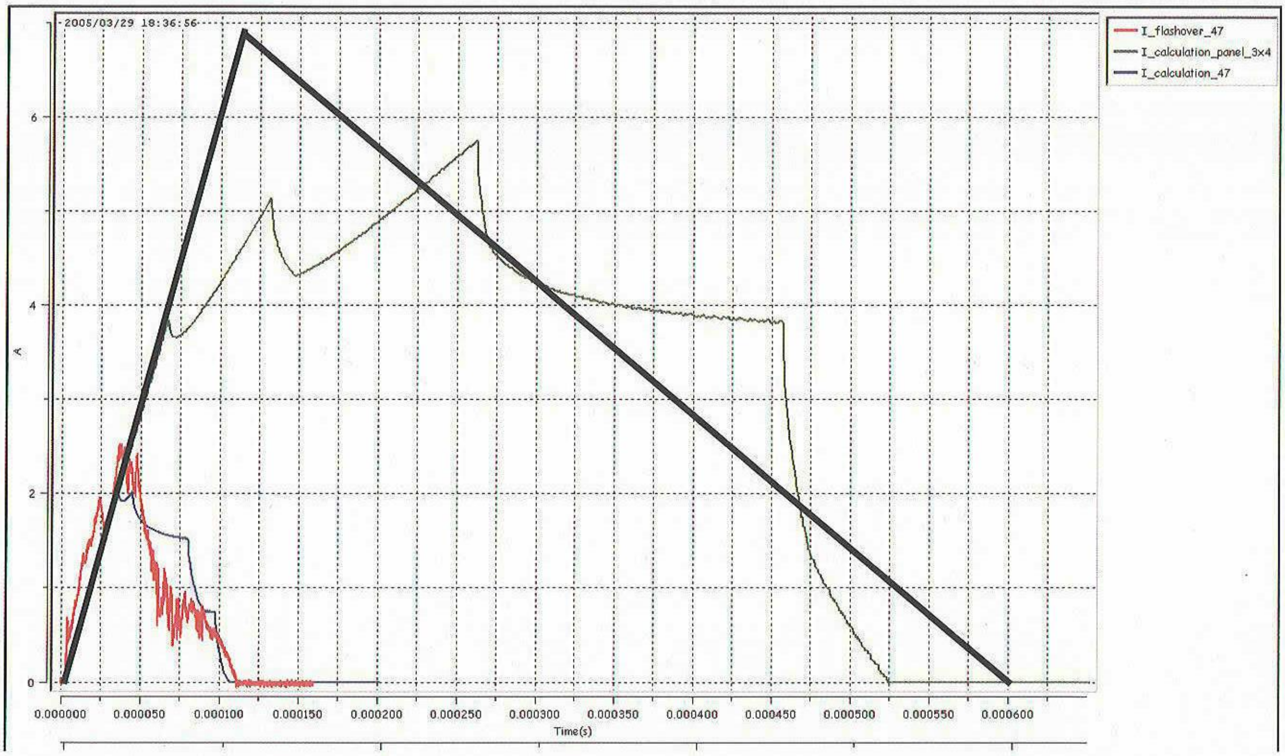


Figure 18: Flashover discharge example which could occur on a 3x4m solar panel: current calculation from perimeter calculation: the discharge lasts 520μs and has a peak current of 5.7A. Dissipated charges calculated are around 1,91mC. One can say from calculation on discharge n°47 that I-peak should be higher. Suggested flashover current simulation for a 12m² panel: peak current: 6.5A obtained after 110μs, duration: 600μs.

5. CONCLUSION

Experiments on laboratory show that electrostatic discharges triggered by inverted voltage gradient situation can produce neutralization over 1 m². Flashover discharges lasting 120μs and having currents up to 3A, and dissipated charges up to 120μC were observed. Current measurements and calculations show that electron neutralization and plasma neutralization take place during the discharge. Since tests didn't show any neutralization area limitation, one can assume that an electrostatic discharge can neutralize by its flashover current an entire panel. Calculation for a 3x4 m² solar panel gives flashover current up to 6A and discharge duration up to 520μs. So, electrostatic tests and secondary arcs tests should take care at simulating flashover current and take as a worst case maximum peak current, maximum lifetime, rise-time and dissipated charges. For instance, CNES propose a test set-up characterized by a maximum current of 6.5A, and a lifetime around 600μC.

Acknowledgments: the same kind of experiments have been performed at KIT (Kyushu Institute of Technology) in Mengu Cho laboratory on a similar solar array coupon (size 400x400mm) and aim to set an international standard for ESD and secondary arc tests. Authors thanks Mr. Kunio Kamimura from Sharp Corporation and Mr. Bernard Boulanger from Alcatel Space for providing the large solar array coupons.

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