Secondary arcing triggered by hypervelocity impacts on solar panel rear side cables with defects - Comparison with laser impacts

Jean-Michel Siguier, Virginie Inguibert, Gael Murat, Denis Payan

► To cite this version:

Jean-Michel Siguier, Virginie Inguibert, Gael Murat, Denis Payan. Secondary arcing triggered by hypervelocity impacts on solar panel rear side cables with defects - Comparison with laser impacts. IEEE Transactions on Plasma Science, 2017, 45 (8), pp.1880 - 1886. 10.1109/TPS.2017.2686602 . hal-01371907v2

HAL Id: hal-01371907

<https://hal.science/hal-01371907v2>

Submitted on 9 Feb 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Secondary Arcing Triggered by Hypervelocity Impacts on Solar Panel Rear-Side Cables With Defects—Comparison With Laser Impacts

Jean-Michel Siguier, Virginie Inguibert, Gaël Murat, and Denis Payan

Abstract—High-velocity impacts of micrometeoroids and debris are proven causes of solar arrays power loss. Many studies have been carried out in this domain with relatively large size particles, in the range of 1 mm, causing obviously large damages, but with a small probability of occurrence. This paper deals with the occurrence of secondary arcing triggered on solar panel rear face cables with defects (lack of dielectric envelope) by smaller particles, in the range of 20–80 μm (20 to 5 km/s), that is, with a probability of impact of several hundred of impacts by m^2 and by year both in low earth and geostationary orbits. Plasmas produced by high-velocity impacts on metallic (aluminum) and dielectric (Kapton) surfaces are characterized with a Langmuir triple probe (temperature, density, floating potential, and escape velocity). Secondary arcing tests on rear-side cables with cracks under high-velocity impacts are achieved using a solar array simulator with realistic in flight electrical conditions (120 V^{-1} to 3 A). Secondary arcing tests and plasma characterization are also carried out with laser impacts (0.2 J YAG laser) and compared with high-velocity impacts.

Index Terms—Arcing, high-velocity impact, laser, micrometeoroid and debris (MMD), plasma, secondary arc, solar array.

I. INTRODUCTION

SECONDARY arcing is a well-established cause of power loss on solar arrays and its occurrence is still largely studied because manufacturing and electric conditions are always evolving. If the main cause of primary arcing, which may lead to secondary arcing, is due to electrostatic discharges (ESDs), another one is attributed to micrometeoroid and debris (MMD) impacts. Many studies carried out with large-size projectiles (>1 mm) have determined that hypervelocity impacts (HVIs) create, in both sides of a solar array, defects and plasma at the same time, which may trigger a secondary arc between polarized and nonprotected metallic elements [1]–[4]. Other studies performed with smaller projectiles in the range of 40–500 μm impacting solar cell or harness coupons showed very dispersive results: inconclusive [5], without any secondary arc [6], temporary sustained arc (TSA) [7], and permanent sustained arc (PSA) but with a very high (≈ 8 A) solar array simulator (SAS) value [8].

Manuscript received July 4, 2016; accepted March 13, 2017.

J.-M. Siguier, V. Inguibert, and G. Murat are with the DESP-UFT-MiP, ONERA, 31400 Toulouse, France (e-mail: jean-michel.siguier@onera.fr).

D. Payan is with CNES, F-31401 Toulouse, France.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TPS.2017.2686602

Fig. 1. Langmuir triple probe.

This paper deals with the possibility to trigger secondary arcs on solar arrays with impacting particles in the range of 20–80 μm and to compare these HVIs with laser impacts in order to have a more simple way to carry out experimentation than using a high-velocity impact facility.

The range 20–80 μm is chosen because the probability is rather important (a few 100 impacts/ m^2/year) compared with 1-mm-size particles ($\approx 10^{-2}$ impacts/ m^2/year) and the plasma produced by the impact is supposed to be dense enough to trigger an arc [9].

Secondary arcs are performed on back-side solar array cables with defects, that is, between stripped parts of two cables polarized with an SAS.

In a first step, plasmas produced by the impact of glass projectiles on aluminum and Kapton surfaces are characterized by a triple Langmuir probe and compared with plasmas produced by laser impacts on the same surfaces.

In a second step, secondary arcs tests are performed with HVI and laser impacts on a stripped back-side cable.

II. HVI PLASMA CHARACTERIZATION

A. Triple Probe

The Langmuir triple probe we used for plasma characterization is shown in Fig. 1 and the setup in Fig. 2. Each electrode is a metal covered with carbon powder, having a length of 16 mm and a diameter of 2.2 mm. The V_{21} and V_{31} values are 1.5 V and 9 V. R is from 100 Ω to 1 k Ω depending on plasma density. The oscilloscope, insulating from ground, measures the voltages induced by the three currents through the resistors. For high plasma densities (i.e., laser impacts), the three resistors and the floating oscilloscope are suppressed and replaced by transient current probes connected to a regularly grounded oscilloscope.

Fig. 2. Triple probe setup.

Fig. 3. Mass/velocity distribution of the TUM/LRC plasma dynamic accelerator of TUM/LRT [8].

Triple probe theory is described in [10]. From current measurements, we deduce electron temperature T_e , plasma density N_e , and floating potential V_f of the transient plasma. Calculations are detailed in [11]. The response time of the circuit is better than 1 μ s.

B. HVI Facility

The HVI facility used for this study is a plasma dynamic accelerator located at Technical University of Munich (TUM) and provides an HVI of a glass sphere from 20 to 80 μ m with a corresponding velocity of 2–20 km/s, as seen in Fig. 3. The impact location is within a diameter of 5 cm.

C. HVI Plasma Results

The triple probe is set at about 5 cm from the aluminum or Kapton film, but due to the uncertainty of the impact location (within an area of 5×5 cm²), the impact–probe distance may vary from 3 to 8 cm. Several shots are performed and the velocity is measured for each shot in order to verify an average velocity of 7.1 km/s, which gives, from Fig. 3, an average projectile size (glass sphere) of $\varnothing 50$ μ m.

Fig. 4 shows an example of probe currents collected during the shot. During the first 400 μ s, the triple probe is saturated by the incident plasma coming with the glass projectile. The

Fig. 4. Plasma currents collected by the triple probe during an HVI on a 125- μ m Kapton film.

TABLE I

PLASMA CHARACTERISTICS OF HVI ON ALUMINUM

HVI on aluminum	average	standard deviation
T_e	0,9 eV	0,2
N_e	$2,5 \cdot 10^{14} \text{ m}^{-3}$	$1,1 \cdot 10^{14} \text{ m}^{-3}$
V_f	2,8 V	0,7 V

TABLE II

PLASMA CHARACTERISTICS OF HVI ON KAPTON

HVI on Kapton	average	standard deviation
T_e	0,9 eV	0,1 eV
N_e	$3 \cdot 10^{14} \text{ m}^{-3}$	$1,3 \cdot 10^{14} \text{ m}^{-3}$
V_f	2,7 V	0,2 V

impact occurs at about 550 μ s, which gives a velocity of 8.3 km/s and then, from Fig. 3, an estimated projectile size of $\varnothing 60$ μ m $\pm$ 30 μ m. The plasma flow lasts a few tenths of microseconds and reaches a maximum value that is used for plasma parameter calculation.

Tables I and II show the average plasma characteristics of HVI performed on aluminum and Kapton surfaces. Standard deviation is due to both the size/velocity dispersion of different impacts and the noisy signal.

III. LASER PLASMA CHARACTERIZATION

A. Laser Facility

Plasma measurements and arcing tests with laser impact are performed in the JONAS facility (a 9-m³ vacuum chamber) located at DESP/ONERA-Toulouse. Laser is a YAG type providing about 0.2-J focused pulse ($\varnothing \approx 300$ μ m) at 1.05-nm and 20-ns durations.

B. Laser Impact Results

Because collected probe currents are higher than the HVI for the aluminum plate and because there is more space in the facility to set several triple probes, a more significant study is carried out on laser plasma characterization. In this aim, two triple probes are set at different distances from the impact location in order to measure the plasma characteristic function of distance to the impact location and the plasma escaping velocity.

Fig. 5. Collected currents at 3 cm from the laser impact with plasma parameter calculations at two different times.

Fig. 6. Collected currents at 24 cm from the laser impact and time delay evaluation with the probe at 3 cm (only I1 of the probe set at 3 cm is represented).

Fig. 7. Electron temperature of laser impact plasma on aluminum function of distance (probe 1 in black and probe 2 in red).

Examples of plasma currents, collected by the triple probes after laser impact, are shown in Figs. 5 and 6.

Fig. 5 shows probe currents versus time and plasma characteristics calculated at $t_0 + 0.5$ ms and $t_0 + 1.5$ ms.

Fig. 6 shows probe currents of two probes set at different positions from another laser impact. The first probe is set at 3 cm and the second one at 24 cm. Plasma characteristics are calculated at the maximum current values (time = 5 μs).

Measurements performed at different distances from the impact location show temperature, density, and floating potential evolution versus the distance in Figs. 7–10.

IV. TOTAL EMITTED CHARGES CALCULATION

Widening of the current pulse between the 3-cm distance and the 24-cm distance probe in Fig. 6 means that the plasma produced by the impact is escaping with a distribution of velocities. The velocity of the maximum of distribution

Fig. 8. Floating potential of laser impact plasma on aluminum function of distance.

Fig. 9. Density of laser impact plasma on aluminum function of distance.

Fig. 10. Density of laser impact plasma on aluminum function of $1/d^2$.

is 85 ± 10 km/s, in the same range as measured in [12]. This means that the triple probes measure an instantaneous charges density. Fig. 10 shows that the expansion is spherical so, with some geometric approximations, and considering a directivity θ of the emitted plasma as seen in [12], we can calculate the total emitted charges by the laser impact Q , following the model of Fig. 11:

$$Q = \theta \int_t n(t) \cdot V \cdot dt \approx \theta \int_t n(t) \cdot S \cdot v \cdot t \cdot dt \quad (1)$$

where

- Q total number of emitted charges;
- V volume crossed by the charges;
- $n(t)$ local charge density measured by the probe as a function of time;
- v average escaping velocity of the charges;
- S surface of the semisphere.

That is, with discrete time steps

$$Q \approx \theta \cdot 2\pi \cdot R^2 \cdot v \cdot \sum_i N(\Delta t_i) \cdot \Delta t_i. \quad (2)$$

Fig. 11. Plasma escape model.

TABLE III

COMPARISON OF HVI AND LASER PLASMA FOR ALUMINUM AT 5 cm

aluminum :	HVI	Laser
T_e	0,9 eV	2 eV
N_e	$2.5.10^{14} \text{ m}^{-3}$	3.10^{18} m^{-3}
V_f	2,8 V	7 V

TABLE IV

COMPARISON OF HVI AND LASER PLASMA FOR KAPTON AT 5 cm

Kapton 125 μm :	HVI	Laser (no perforating)	Laser (perforating)
T_e	0.9 eV	1.1 eV	0.6 eV
N_e	3.10^{14} m^{-3}	$1.6.10^{16} \text{ m}^{-3}$	3.10^{15} m^{-3}
V_f	2.7 V	3.3 V	1.6 V

This plasma expansion model is also applied to HVI charge calculations. In this case, according to [9], the plasma expansion velocity is estimated equal to the impact velocity.

V. COMPARISON BETWEEN HVI AND LASER IMPACT PLASMA

The plasma characteristics produced by HVI and laser impacts, measured at 5 cm from the impact location, are summarized in Table III for the aluminum target and Table IV for the Kapton target.

As we can see in Tables III and IV, laser impacts (0.2 J) produce much more plasma than HVI (glass, 50 μm , 7 km/s). Laser impact plasma strongly depends on the target material, which is not the case for HVI on aluminum and Kapton. For a perforating laser impact on Kapton, we suppose that a part of the produced plasma is trapped on the back side and so less plasma is measured in the front side.

Plasma charges produced by HVI and laser impacts have been largely measured and modeled by empirical equations [13]–[15].

For HVI, the total amount of charges produced is

$$Q(C) = 1.3.10^{-4} \text{ m}^\alpha \text{ v}^\beta \quad (3)$$

where

- m projectile mass (g);
- α =0.95 (for our conditions);
- v velocity (km/s);
- β =3.5 (for our conditions);
- Q is divided by 5 if the target is dielectrics. The nature of projectile is without effect on plasma production [14].

TABLE V
COMPARISON OF TOTAL EMITTED CHARGES FOR
HVI, LASER IMPACT, AND ESD

	Incident energy	Q calculated with (3),(4) or (5)	Q measured and calculated with (2)
HVI ($\emptyset 50 \mu\text{m}/7\text{km/s}$) on aluminum	$0.4\text{mJ} < Q < 25\text{mJ}$	$25\text{nC} < Q < 140\text{nC}$	$9\text{nC} < Q < 100\text{nC}$
HVI ($\emptyset 50 \mu\text{m}/7\text{km/s}$) on Kapton	$0.4\text{mJ} < Q < 25\text{mJ}$	$5\text{nC} < Q < 30\text{nC}$	$11\text{nC} < Q < 120\text{nC}$
Laser (0.2 J, 20 ns, 0.03mm^2) on aluminum	200 mJ	110 μC	150 μC
Laser (0.2 J, 20 ns, 0.03mm^2) on Kapton	200 mJ	50 μC	120 μC
ESD 100pF	50 μJ	100 nC	
ESD 150nF	75 mJ	150 μC	

For laser impact, the total amount of charges produced is (first level of ionization)

$$Q(+) (\text{mC}/\text{mm}^2) = 0.58 \ln(E_1/E_0) \quad (4)$$

where

- E_0 threshold depending on target nature;
- E_0 =1.0 GW/cm² for semiconductors (C, Si);
- E_0 =1.5 GW/cm² for metals;
- E_0 =4.0 GW/cm² for dielectrics;
- E_1 laser pulse density.

$$E_1 \left(\frac{\text{GW}}{\text{cm}^2} \right) = \frac{W}{t \cdot S} 10^{-9} \quad (5)$$

where

- W laser pulse energy (J);
- t pulse duration (s);
- S impact surface (cm²).

Table V compares the total number of plasma charges produced by HVI and laser impacts. Charges released by a 50- μm HVI are comparable to an ESD of 100 pF ($\approx$ geostationary orbit satellite capacitance) at 1 kV and charges released by a 0.2-J laser impact are comparable to an ESD of 150 μF ($\approx$ low earth orbit satellite capacitance) at 1 kV. Range values for HVI correspond to uncertainty on projectile size and impact–probe distance. HVI presents a good matching between the calculated and measured values. The difference between the calculated and measured values for laser impact may be due to the uncertainty on emitted plasma directivity.

VI. ARCING TESTS

The main point of this paper is to determine if HVI of 20–80 μm particles are able to trigger secondary arcs on cables presenting unprotected parts due to aging, manufacturing conception, or defects as it may happen on rear-side solar panels.

Fig. 12. Secondary arcing test sample. The stripped cables are separated by 1.8 mm.

Fig. 13. Setup for secondary arcing tests.

This kind of test was already performed in our laboratory on cables with cracks but with a secondary arc triggered by ESD in inverse potential gradient situation [16]. It showed that different types of secondary arcs occurred for specific voltage/current values of SAS. The results are as follows.

- 1) SAS = 120 V/1 A, nonsustained arc relative to primary arc duration.
- 2) SAS = 120 V/2 A, temporary sustained arc (TSA) relative to primary arc duration.
- 3) SAS = 120 V/3 A, PSA.

In order to be comparative, the same setup and the same SAS values are used in this study. The differences are in the secondary arc triggering mechanism and the tested sample constitution.

A. Secondary Arc Test Sample

The sample is constituted of two stripped Tefzelwires (gauge#20), separated by 1.8 mm and rolled up around two nylon threaded rods in order to maximize the probability of getting an impact onto the cable (Fig. 12). The diameter of the metallic core of the Tefzel cable is about 0.7 mm (see Fig. 14).

B. Secondary Arc Test Setup

The setup (Fig. 13) is similar to [16]. The SAS voltage is set to 120 V and R_c controls the current in the cables from 1–3.5 A (maximum bearable by our SAS).

C. Arcing Tests With HVI

An example of impact damage on the metallic part of the Tefzel cable is shown in Fig. 14.

For arcing tests, 43 shots have been performed and 15 shots impact the cables. Table VI summarizes the results of HVI

Fig. 14. HVI damage of a glass sphere (between 20 and 80 μm) on a stripped Tefzel cable.

TABLE VI
SUMMARY OF SECONDARY ARC TESTS WITH HVI ON CABLES

SAS values	Shot #	Impact velocity (km/s)	Arc duration (μs)	V_{arc} (V)
120 V-1.2 A	2	4.5	800	?
	5	3.1	80	40
	13	7.8	500	55
	14	1.4	120	40
	15	8.8 et 5.7 (2 impacts)	40 and 60	30 and 40
120 V-2 A	17	8	1400	60
	19	4.3	400	60
	20	3	280	50
120 V-3 A	22	6	80	70
	24	3.8	2000	50
	32	5.4	720	45
120 V-3.5 A	33	5.3	500	60
	36	5.6	600	50
	37	4.8	400	30
	41	7.4	600	30

secondary arc tests. It presents the duration and voltage of secondary arcs for increasing SAS current values. Every HVI on cables triggers a secondary arc. As the primary arc duration (=HVI plasma duration) is about 20 μs (see Fig. 4), every arc is a TSA. It is remarkable that with a quite low SAS current value, only 1 A, we get pretty long duration secondary arc (1.4 ms), but secondary arc duration does not increase with SAS current as it occurs usually. Unlike secondary arc tests triggered by ESD, even high SAS current values (>3 A) do not trigger PSA, but we explain it in Section VII by the sample constitution.

Fig. 15 is an example of currents and voltage measured when an HVI reaches the cable. The “parasitic” incident plasma coming with the high-velocity particle is able to initiate an arc but not to completely establish it.

D. Arcing Tests With Laser Impact

The results of secondary arcing tests triggered by laser impacts are summarized on Table VII.

As for HVI arcing tests, each impact triggers a secondary arc. The secondary arc duration increases with SAS current values. Primary arc duration is here less than 4 μs , as seen

Fig. 15. Example of secondary arc due to HVI (SAS: 120 V/3.5 A).

TABLE VII

SUMMARY OF SECONDARY ARC TESTS WITH LASER SHOTS ON CABLES

SAS values	shot #	Arc duration (μ s)	V_{arc} (V)
120 V-1.2 A	1	50	55
	2	100	60
	3	180	60
	4	35	40
	5	60	30
	6	60	55
	7	100	55
	8	150	55
	9	70	50
	10	30	30
120 V-2 A	1	50	40
	2	150	55
	3	160	50
	4	80	60
	5	150	60
120 V-3 A	1	740	45
	2	1000	45
	3	1150	40
	4	850	50
120 V-3.5 A	5	650	40
	1	650	50
	2	650	50
	3	2900	25
	4	4700	25
	5	1800	25
	6	3200	25
	7	1900	25
	8	400	25

by the probe at 3 cm in Fig. 5, so every secondary arc is considered as a TSA, as for HVI impact.

VII. DISCUSSION

The main result of this paper is that even a “small” high-velocity particle triggers a secondary arc between two stripped cables. Unfortunately, because of the strong directivity of emitted plasmas, both for HVI and laser impacts, it is not possible from our results to extrapolate what is the plasma density at 1.8 mm from the impact location, which triggers secondary arc.

The situation of two adjacent stripped polarized cables is not so common in solar panel rear sides, but due to aging and other possible sources of defects, it is realistic. Thus, considering the large probability of “small” MMD impacts, the risk of secondary arc occurrence has to be considered seriously.

The fact that no PSA was triggered with relatively high SAS current values can be explained by the sample constitution. In this study, the cables are completely stripped in order to increase the probability of impact and thus the secondary arcing occurrence possibility. In ESD triggered secondary arc tests, leading to PSA [16], [17], only a small length of the cables (<10 mm) is stripped and the rest of the cable is still covered with a dielectric sheath. The core of the cable is not able to provide, by cathodic spot emission, enough metallic vapors to maintain an arc pressure. A gas inflow as for plasma torch [18] or an expendable “wall” material [19] as the Tefzel sheath is necessary to feed and thus maintain an arc. Here, once all the oxides and contaminants of the metal core surface are evaporated, the arc stops.

Concerning the simulation of HVI by laser impacts for arcing tests and considering only plasma production—mechanical effects are obviously strongly different—we can say that for this range of particles ($\varnothing 20\text{--}80\ \mu\text{m}$), the results are as follows.

- 1) For any kind of target materials, plasma densities are higher with a 0.2-J laser beam, but it is possible to reduce the plasma produced by the laser with an attenuator or by defocusing the beam.
- 2) Plasma temperatures are quite similar.
- 3) Although we did not investigate this point, it is known that the directivity of the emitted plasma is sharper with laser beam than with HVI due to the fact that laser beam gives a higher kinetic energy to the plasma [12], [20].
- 4) Plasma escape velocities are higher with a laser beam than with HVI [12], [20].

Considering all these remarks and the very similar results we got in secondary arc testing, it is possible to perform secondary arcing tests with laser impacts simulating HVI, providing that HVI defects are already simulated and that the coupon geometry does not present plasma directivity dependence.

VIII. CONCLUSION

Section II analyzes and compares the plasma produced by HVIs ($\varnothing 20\text{--}80\text{-}\mu\text{m}$ projectiles) and laser impacts (0.2-J pulses). Plasma characteristics (temperature, density, and floating potential) are measured with a triple probe. The total number of charges produced by both impact types is deduced from triple probe measurements and compared with theory.

Section III presents the results of secondary arcing tests, triggered by HVI and laser impacts, performed on stripped solar panel cables. Temporary sustained arcs are detected with both high-velocity and laser impacts, for realistic SAS values starting from 100 V/1 A. Permanent arcs would have certainly occur, as for ESD induced secondary arc tests, if the sample were not modified for practical reasons.

The comparison between high-velocity and laser impacts for secondary arc testing is also discussed.

ACKNOWLEDGMENT

The authors would like to thank Dr. M. Rott of LRT, TUM, Germany, for making the plasma dynamic particle accelerator facility available.

REFERENCES

- [1] T. Harano *et al.*, "Preliminary study on sustained arc due to plasma excited by hypervelocity impact of space debris on the solar array coupon," *Int. J. Impact Eng.*, vol. 33, nos. 1–12, pp. 326–334, Dec. 2006.
- [2] R. Putzar, F. Schaefer, and M. Lambert, "Vulnerability of spacecraft harnesses to hypervelocity impacts," *Int. J. Impact Eng.*, vol. 35, no. 12, pp. 1728–1734, Dec. 2008.
- [3] Y. Akaoshi *et al.*, "Influence of space debris impact on solar array under power generation," *Int. J. Impact Eng.*, vol. 35, no. 12, pp. 1678–1682, 2008.
- [4] S. Fukushima *et al.*, "Solar-array arcing due to plasma created by space-debris impact," *IEEE Trans. Plasma Sci.*, vol. 36, no. 5, pp. 2434–2439, Oct. 2008.
- [5] *Hypervelocity Impact Studies of High Voltage Solar Array Segments*, Int. Astron. Congr., Houston, TX, USA, 2002.
- [6] S. Kawakita *et al.*, "Discharge of spacecraft solar panels by hypervelocity impact," *Trans. Jpn. Soc. Aeronaut. Space Sci. Space Technol. Jpn.*, vol. 7, no. 26, pp. Tr253–Tr256, 2009.
- [7] M. J. Neish, M. Takahashi, H. Maejima, H. Kusawake, S. Kawakita, and T. Goka, "Tests to Assess the Vulnerability of ADEOS-2 and ETS-8 to Debris and Micrometeoroid Impacts," presented at the 4th Eur. Conf. Space Debris, 2005, p. 705.
- [8] M. Schimmerohn, *Susceptibility of Solar Arrays to Micrometeorite Impact*, document ESA 22462/09/NL/GLC, 2012.
- [9] H. B. S. Garrett et al., "Impact-induced ESD and EMI/EMP effects on spacecraft—A review," *IEEE Trans. Plasma Sci.*, vol. 41, no. 12, pp. 3545–3557, Dec. 2013.
- [10] S.-L. Chen and T. Sekiguchi, "Instantaneous direct-display system of plasma parameters by means of triple probe," *J. Appl. Phys.*, vol. 36, no. 8, pp. 2363–2375, Apr. 1965.
- [11] V. Inguibert *et al.*, "Measurements of physical parameters characterizing ESDs on solar cell and correlation between spectral signature and discharge position," *IEEE Trans. Plasma Sci.*, vol. 43, no. 9, pp. 2985–2992, Sep. 2015.
- [12] O. Albert *et al.*, "Time-resolved spectroscopy measurements of a titanium plasma induced by nanosecond and femtosecond lasers," *Appl. Phys. A*, vol. 76, no. 3, pp. 319–323, Mar. 2003.
- [13] J. F. R. Kissel et al., "Ion formation by impact of fast dust particles and comparison with related techniques," *Appl. Phys. A*, vol. 42, no. 1, pp. 69–85, Jan. 1987.
- [14] F. R. Krueger, "Hypervelocity impact physics—plasma discharge phenomena on solar generators," in *The Behavior of Systems in the Space Environment*, R. N. DeWitt, D. Duston, and A. K. Hyder, ed. Amsterdam, The Netherlands: Springer, 1993, pp. 273–290.
- [15] P. R. Ratcliff, M. J. Burchell, M. J. Cole, T. W. Murphy, and F. Alladadi, "Experimental measurements of hypervelocity impact plasma yield and energetics," *Int. J. Impact Eng.*, vol. 20, nos. 6–10, pp. 663–674, 1997.
- [16] J.-M. Siguier, V. Inguibert, G. Murat, D. Payan, and N. Balcon, "Study of secondary arcing occurrence on solar panel backside wires with cracks," *IEEE Trans. Plasma Sci.*, vol. 43, no. 9, pp. 2980–2984, Sep. 2015.
- [17] D. Qu *et al.*, "Laboratory test of arcing on satellite power cables," presented at the 9th SCTC, Tsukuba, Japan, 2005.
- [18] J. P. Trelles, C. Chazelas, A. Vardelle, and J. V. R. Heberlein, "Arc plasma torch modeling," *J. Thermal Spray Technol.*, vol. 18, nos. 5–6, pp. 728–752, Dec. 2009.
- [19] C. B. Ruchti and L. Niemeyer, "Ablation controlled arcs," *IEEE Trans. Plasma Sci.*, vol. 14, no. 4, pp. 423–434, Aug. 1986.
- [20] M. J. Rival and C. Mandeville, "Modeling of ejecta produced upon hypervelocity impacts," *Space Debris*, vol. 1, no. 1, pp. 45–57, Mar. 1999.

Jean-Michel Siguier received the Dipl.-Ing. degree from CNAM-Toulouse, Toulouse, France, in 1989.

From 1980 to 1995, he was involved in the development of secondary electronic emission facility and a deep charging facility. From 1996 to 2007, he was with the French Space Agency, CNES, Toulouse, where he was involved in the material characterization for stratospheric ballooning. He has been with the Space Environment Department, French Aerospace Lab, ONERA, Toulouse, since 1979. Since 2008, he has been involved in spacecraft charging, ESD's, and plasma-spacecraft interactions.

Mr. Siguier has served as a referee for the IEEE TRANSACTIONS ON PLASMA SCIENCE.

Virginie Inguibert received the Ph.D. degree from the University of Toulouse, Toulouse, France, in 1995.

She was the Head with the Coupling Satellite-Environment Group in 2009. She was involved in the erosion of polymers by atomic oxygen, characterization of thermo-optical properties of materials, erosion, and contamination of materials submitted to electric propulsion. She has been with the Space Environment Department, French Aerospace Lab, ONERA, Toulouse, since 1996. She has been involved in electrostatic discharge experimental activities since 2002.

Dr. Inguibert has served as a referee for the IEEE TRANSACTIONS ON PLASMA SCIENCE.

Gaël Murat received the technical degree in physical measurements and the License degree in instrumentation and test in complex environments from the University of Toulouse, Toulouse, France, in 2005 and 2006, respectively.

He has been with the Space Environment Department, French Aerospace Lab, ONERA, Toulouse, France, since 2009. He is responsible for JONAS facility, where all ESD tests are performed.

Denis Payan is currently a Senior Expert in spacecraft charging and electrostatic risk and has been with CNES, Toulouse, France, the French space agency, for over 27 years in this field. He is a Project Manager on AMBER plasma sensor, measuring charging plasma aboard commercial spacecraft. He is also a member of the Spacecraft Plasma Interaction Network in Europe.