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THE FRENCH AEROSPACE LAB

Experimental investigation of the initiation of vacuum arcs on solar arrays of satellites

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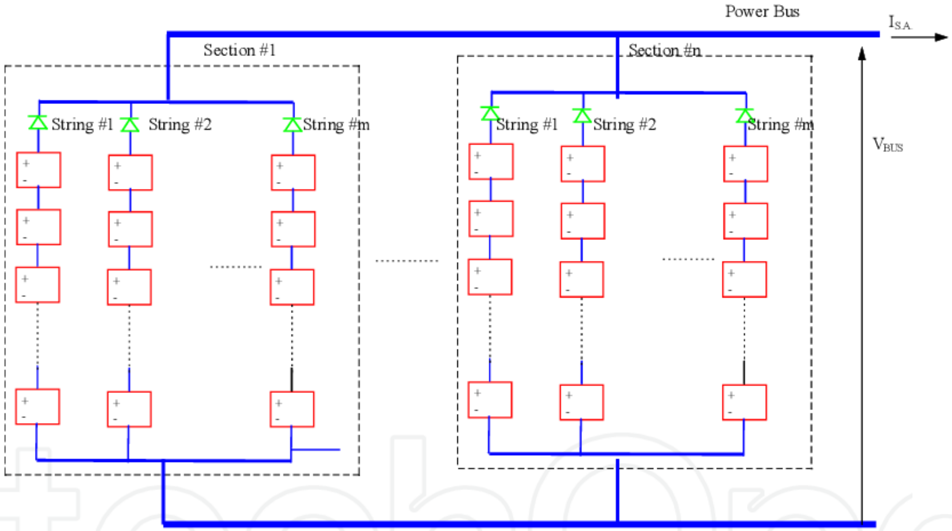
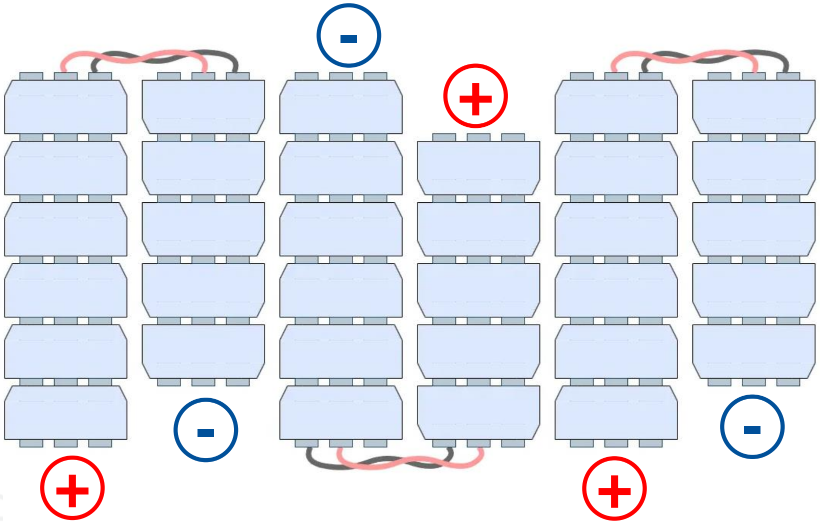
Triggering of arcs on satellite solar arrays?

- Solar array = strings of solar cells in parallel
- String current ~ 0.5-1.5 A
  (section : 3-5 A)
- Layout constraints
  → between 2 strings (gap ~1 mm): ~100 V
- GEO orbit = very high vacuum conditions
- LEO orbit : low density plasma (n_e~10^{11} m^{-3})
- Arc initiation?





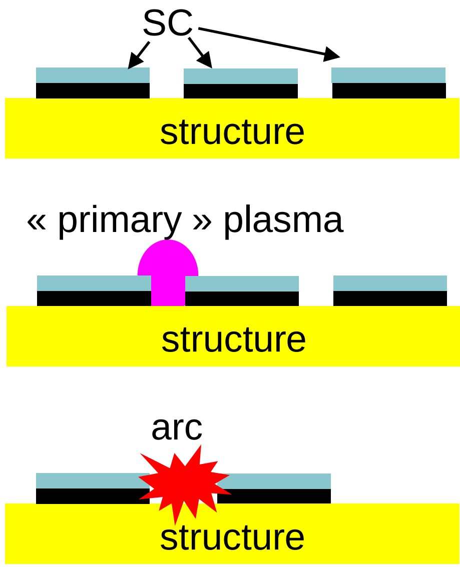
Triggering of arcs on solar arrays!

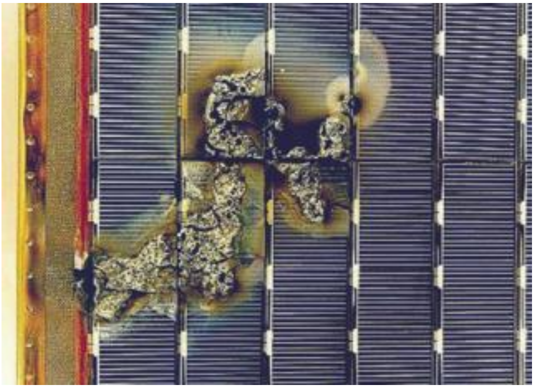
- Risk of arc induced by electrostatic discharges (ESD) or micrometeoroid/orbital debris (MMOD) impact

→ formation of a « primary » plasma = presence of ionized gas between 2 strings of solar cells

→ formation of a « secondary arc »: can damage solar cells if sustained for several ms

- Consequences: decrease of SC efficiency, cable/connectors disruption, loss of electrical insulation→ loss of electrical power
- Need of methods to qualify solar array : evaluation of arc risk and possible damages
- Evaluation of risk: simulation (charging) + qualification tests (arcs)





ESA/EURECA solar array Flight sample

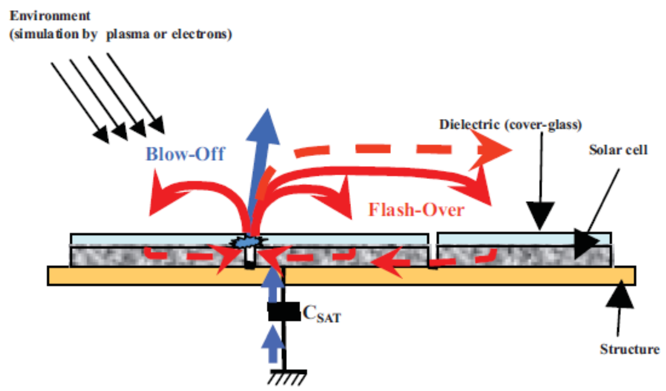
Electrostatic discharges

- Differential charging of satellites surfaces in orbit
- Collection of charged particles → absolute charging of the spacecraft (~ kV, negative)
- Secondary emission and photoemission → positive charging of dielectrics (CG of SCA) wrt/ satellite structure

  « IPG » ~500-1000 V→ promotes production of ESDs
- ESD in the gap between 2 strings → production of a plasma (n_e~10^{20}-10^{25} m^{-3}, Te ~5 eV) during ~ 100 µs
- ESD = expansion of plasma neutralizing dielectrics

  ~ vacuum arc with diffuse (and moving) anode
- Triggering of a secondary arc:

  available current = string or section current
- Arc sustainment depends on numerous parameters: gap, voltage, available current, electrode materials, outgassing…
- Secondary arcing risk must be evaluated after any modification of solar array (operation conditions + SC assembly)



C. Sol, "Simulation of electric arcs and discharge plasma on the solar panels of satellites", Wednesday 06/04 11:30

ESD Test methods

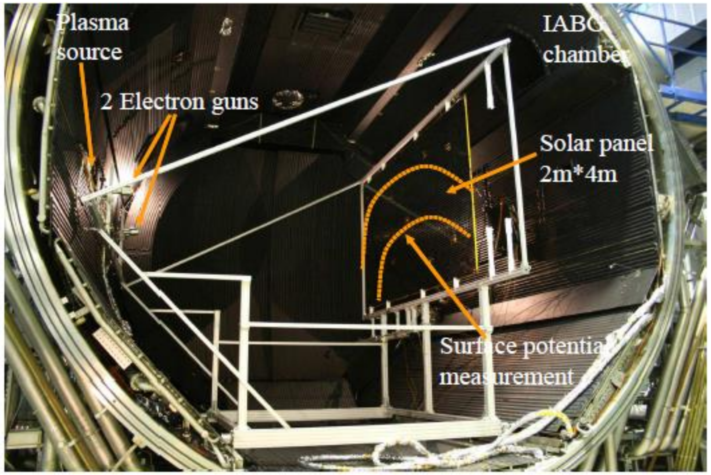
Standardized method for qualification of solar array against ESD / arcing risk in orbit

1. Produce a representative primary plasma

Tests on a real (full scale) solar array is expensive / not always possible → Samples with a few cells

Approach: Produce ESDs with a representative current waveform (amplitude, duration)

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION



2. Simulate electrical circuit of secondary arc

Solar array = DC generator (SAS)

3. Characterize secondary arc (sustained ?) and the possible degradation of solar cells

Avoid over/under-estimation of the risk

ECSS-E-ST-20-06-C Rev.1, “Space Engineering – Spacecraft charging”, 2019
ECSS-E-ST-20-08-C Rev.2, “Space Engineering – Photovoltaic assemblies and components”, 2023
ISO-11221, “Space systems – Space solar panels – Spacecraft charging induced electrostatic discharge test methods,” 2011

Test facility and diagnostics

- Vacuum chamber

JONAS: Ø1,85 m, L=3,5m, P=$2x10^{-7}$ mbar

- Charging methods: HV generators + Plasma source / electron beam / UV source
- Solar array simulators
- Electrical diagnostics
- High speed imaging
- Potential probes, electrostatic probes

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Test methods

<u>1. Produce a representative primary plasma</u>

Approach: Produce ESDs with a representative current waveform (amplitude, duration)

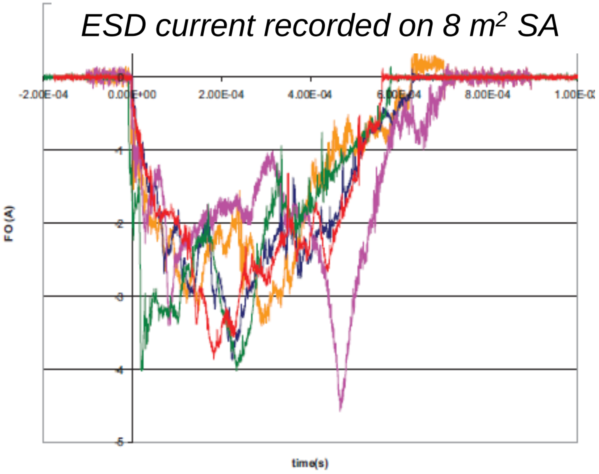
Build potential gradient on the solar cells

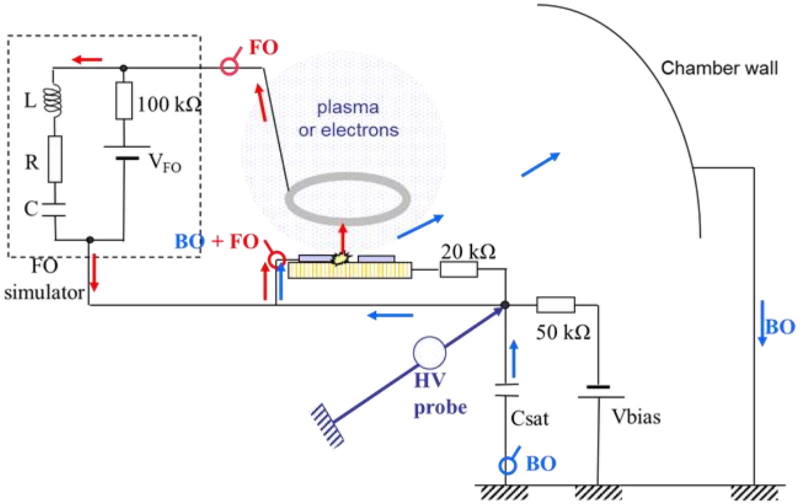
Production of ESD current = BO + FO

Inputs: data from test campaigns on a 8 m^2 solar array

→ Electrical circuit : FO simulator

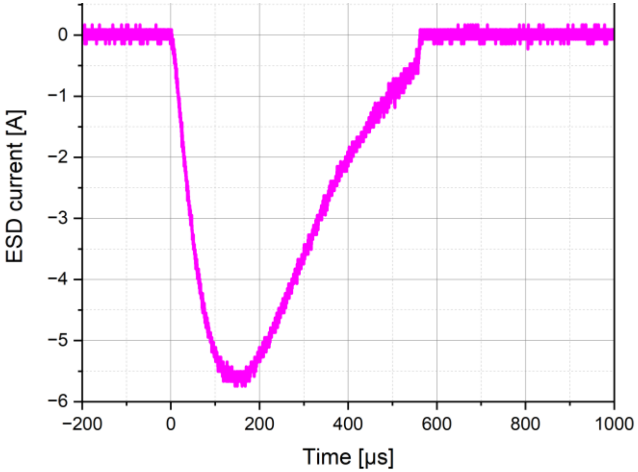
ESD current recorded on 8 m² SA





V. Inguimbert et al., IEEE Trans. Plasma Sci. 2013

ESD current produced by FO simulator



Test methods

2. Simulate electrical circuit of secondary arc on real SA

- Arc current control

SAS = DC generators

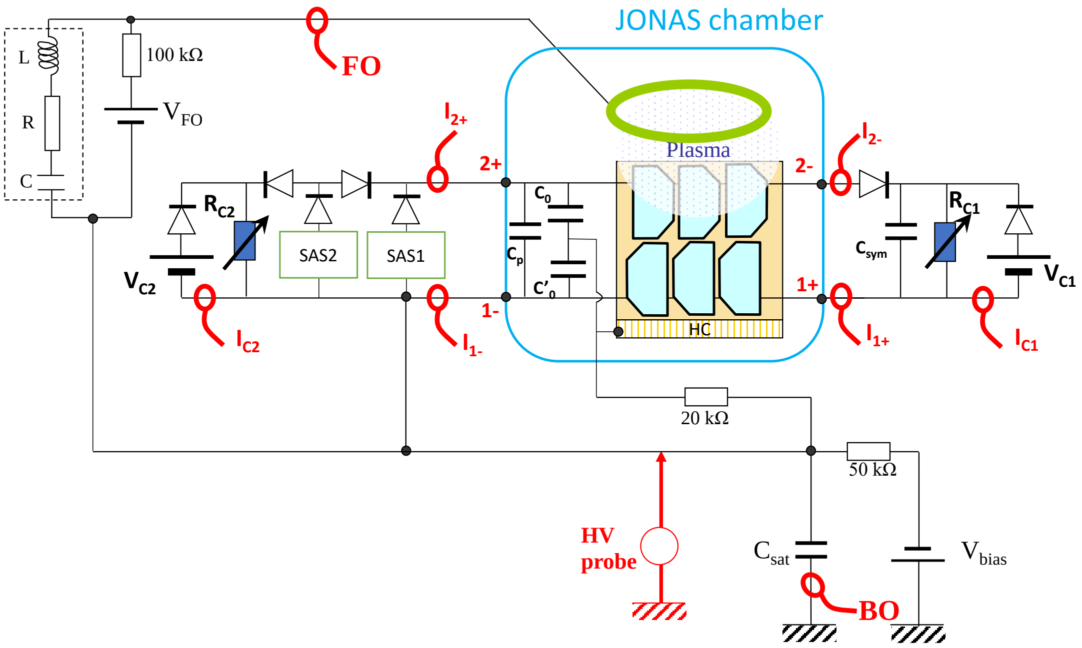
Loops of current during arc phase

- Gap voltage control

- Dynamic behavior (transients)

Parasitic capacitances (String/String, String/structure)

Reduced inductance



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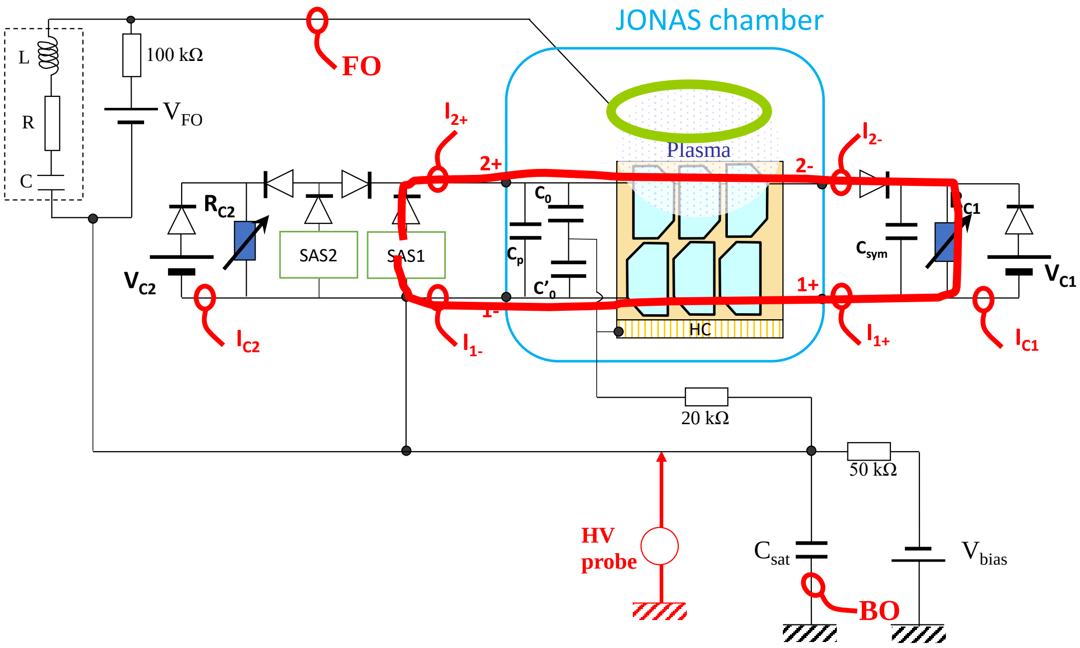

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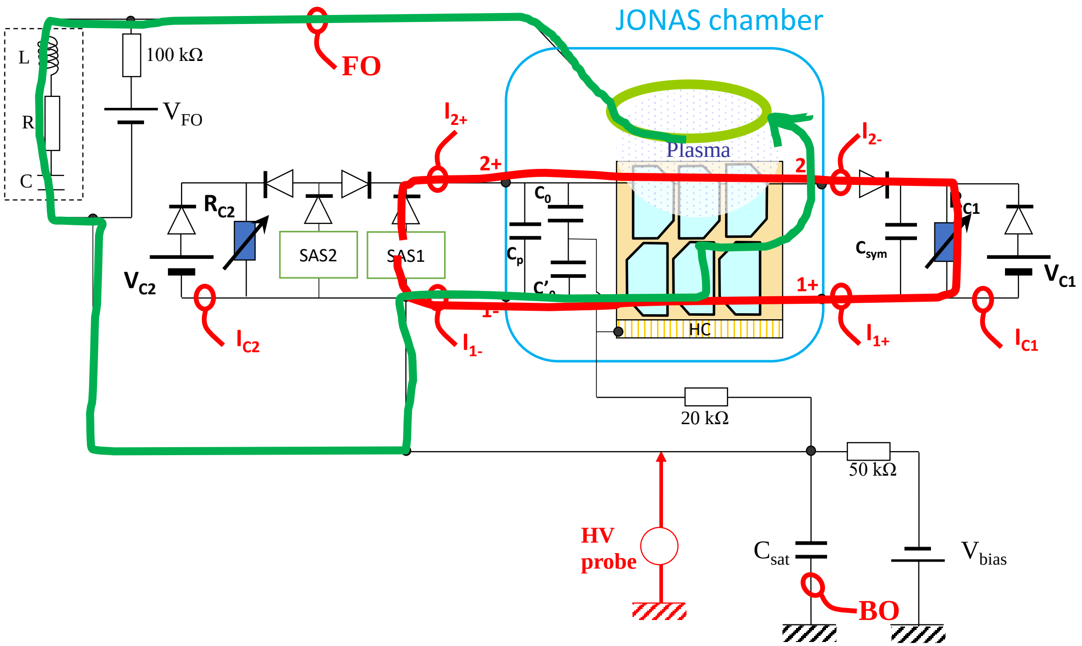

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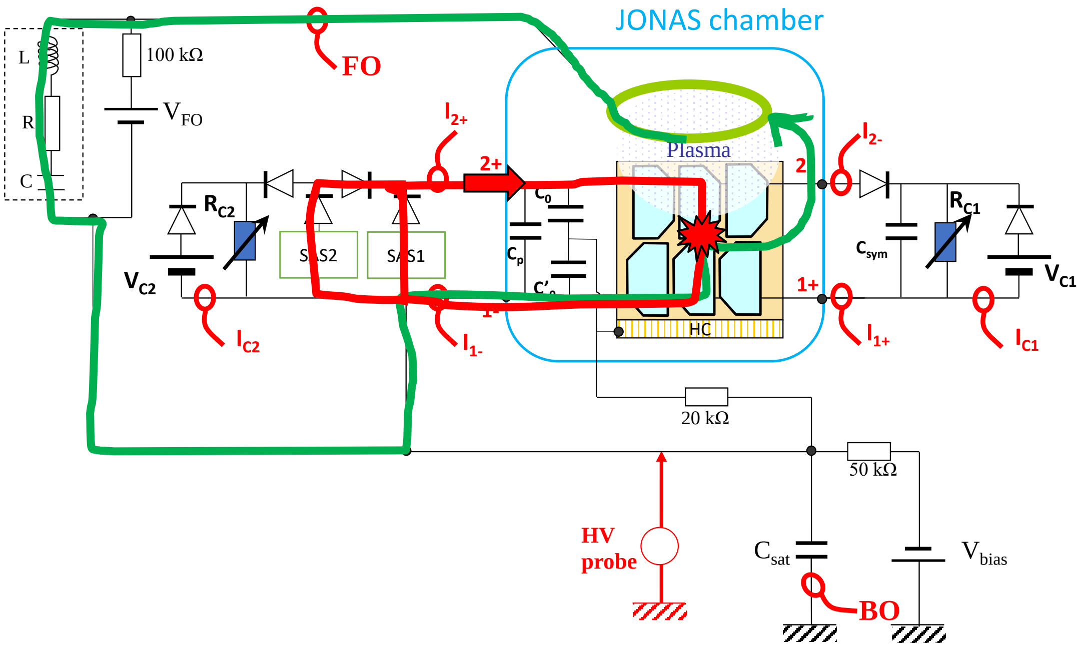
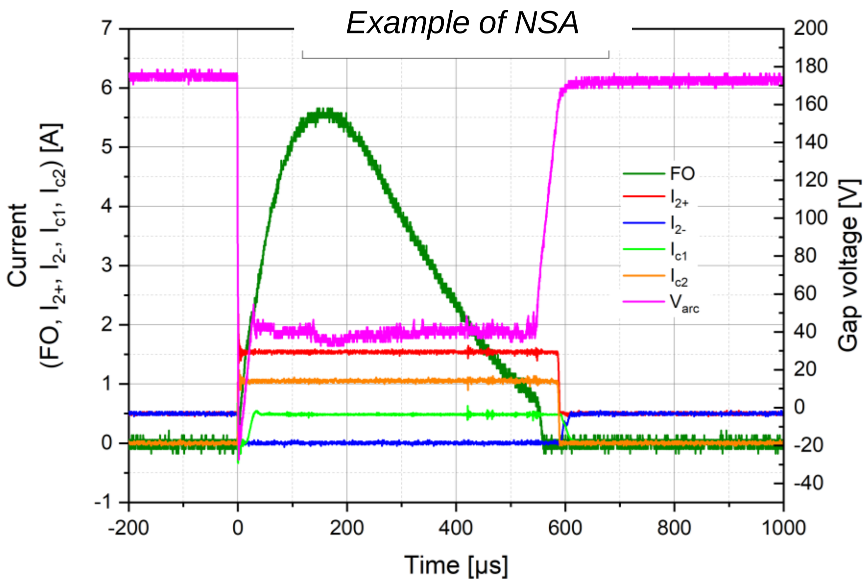


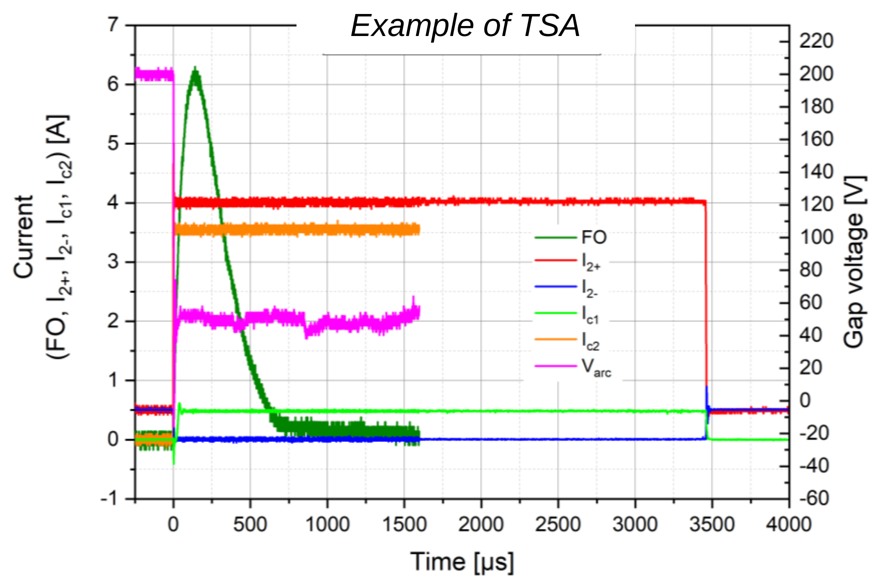
ESD/arcing tests

<u>3. Characterize secondary arc:</u>

NSA: Non-Sustained Arc → extinction with ESD

TSA/PSA: Temporary/Permanent Sustained Arc → maintained after ESD extinction



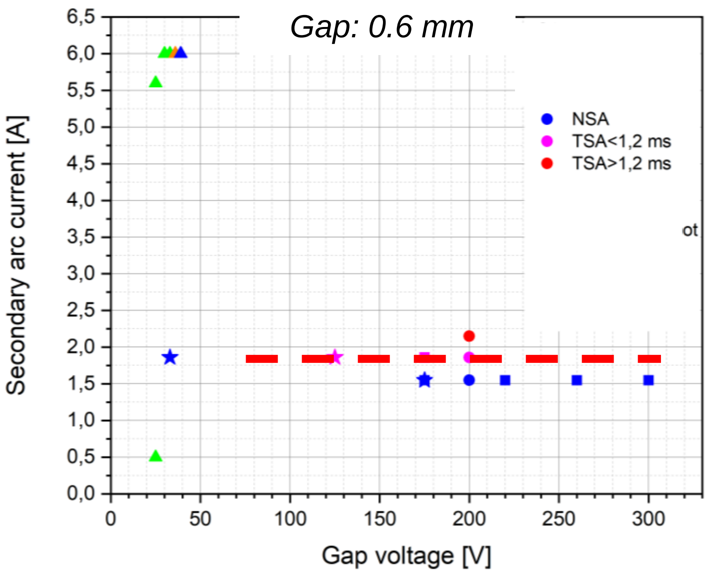


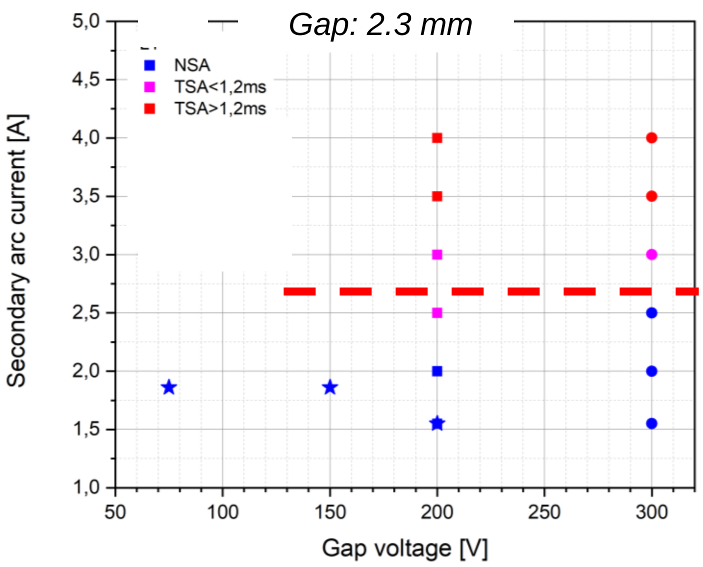
ESD/arcing tests

3. Characterize secondary arc:

Threshold in current for production of sustained arcs

→ higher current helps stabilizing the arc



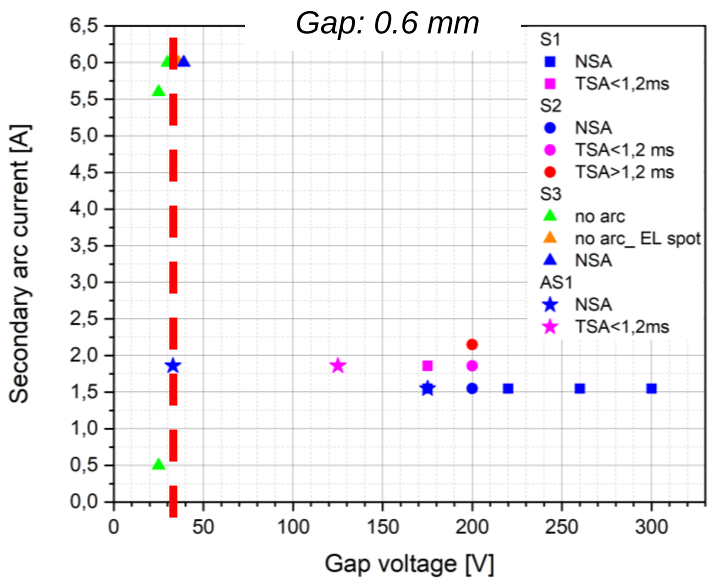


ESD/arcing tests

3. Characterize secondary arc:

Threshold in voltage for production of sustained arcs:

- Gap voltage < anode+cathode drop voltage → no arc is triggered

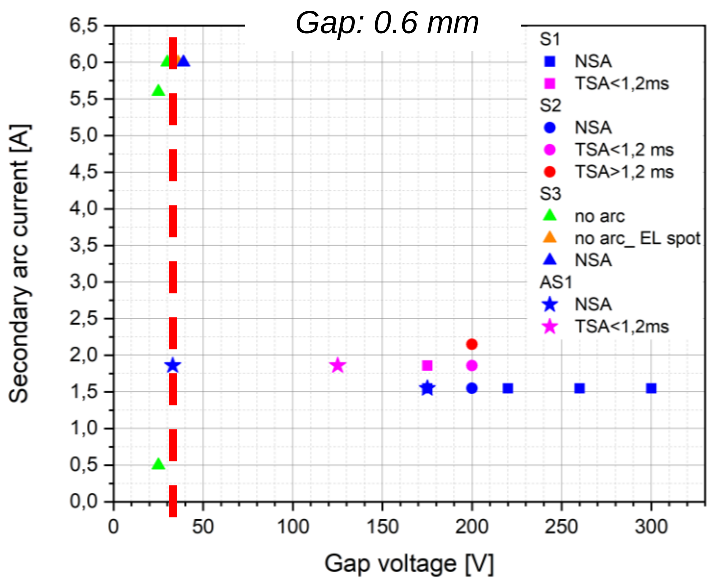


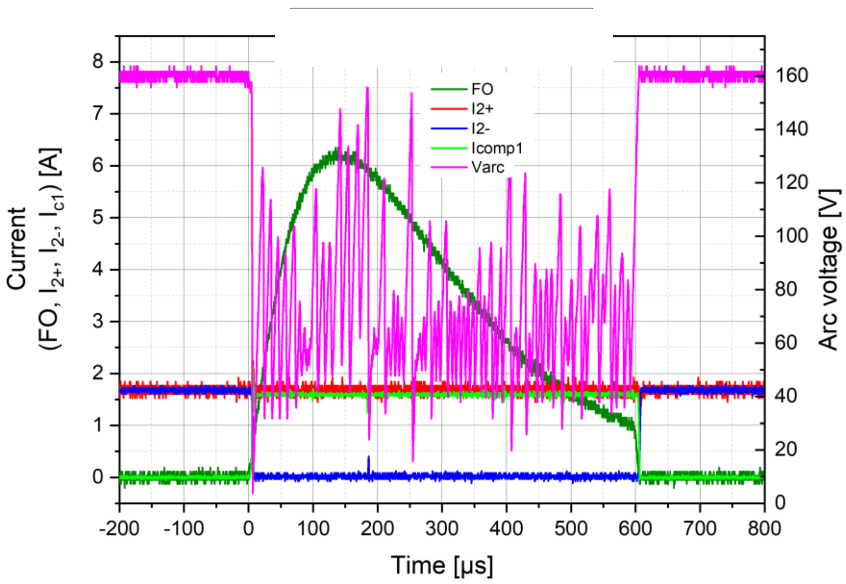
ESD/arcing tests

<u>3. Characterize secondary arc:</u>

Threshold in voltage for production of sustained arcs:

- Gap voltage < anode+cathode drop voltage → no arc is triggered
- Oscillations of arc voltage : if gap voltage < V_{critic} → extinction

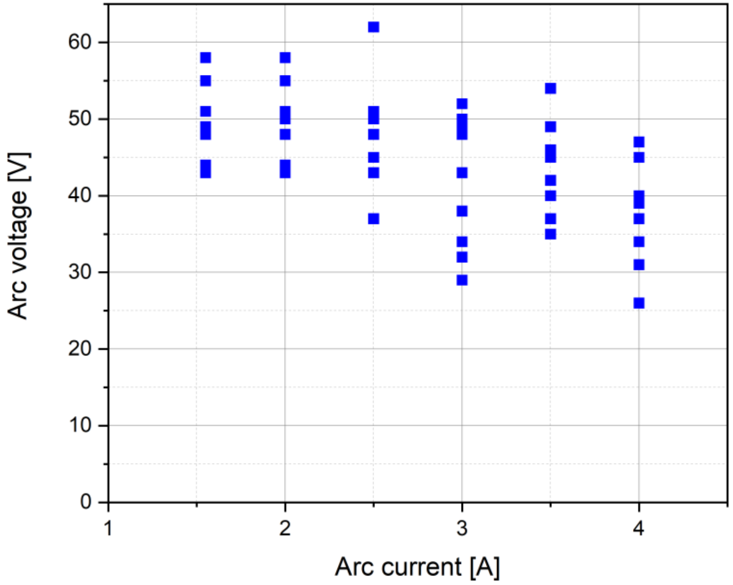


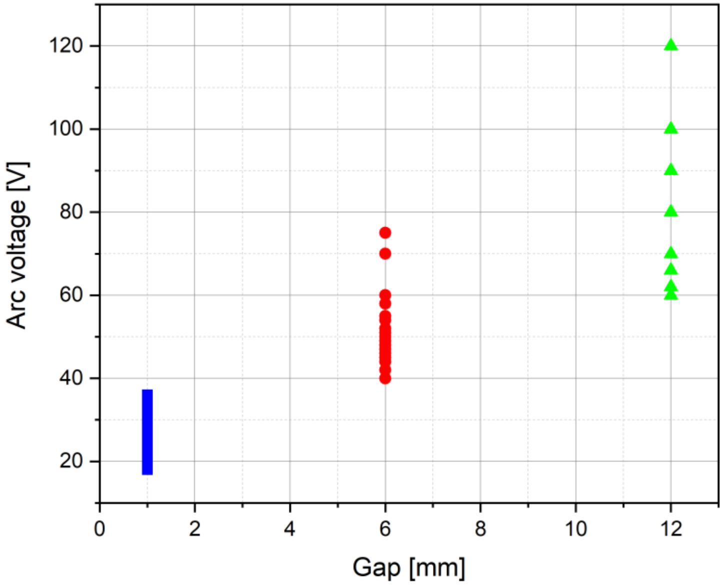


ESD/arcing tests

<u>3. Characterize secondary arc:</u>

Effect of arc current and gap width on arc voltage

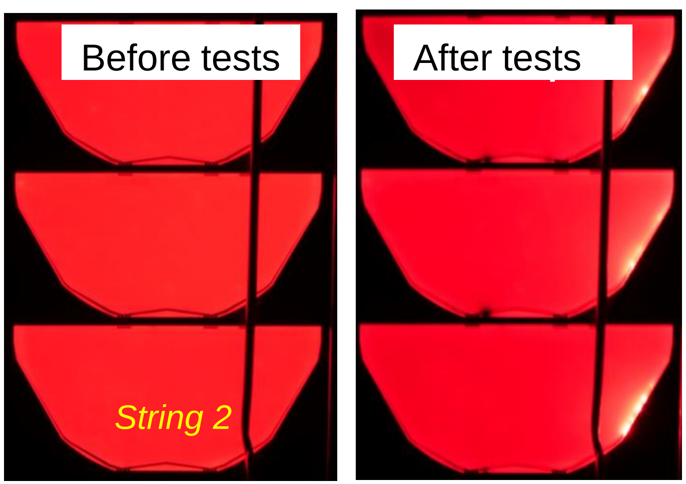




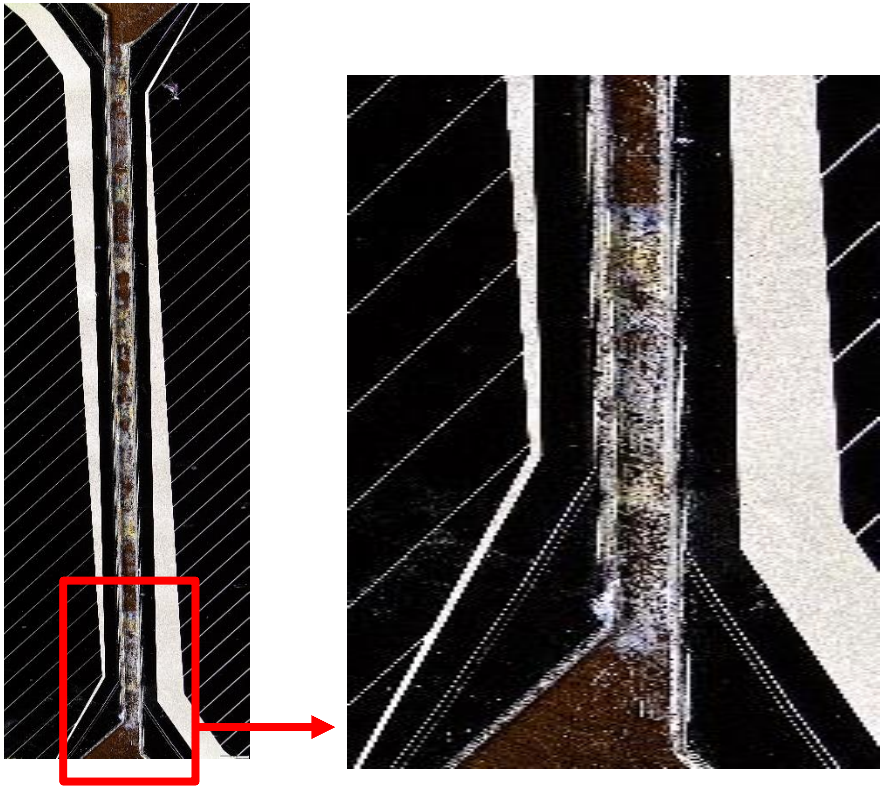
ESD/arcing tests

3. Characterize degradation of solar cells

EL Spot = short-circuit in semi-conductor material
→ Impact on I-V characteristics
→ Formation after secondary arcs with a critical duration
→ Mainly on the anode side



Loss of insulation: deposition of ablated material in the gap
→ Loss of power
→ Risk of short-circuit



Evolution of ESD/arcing tests

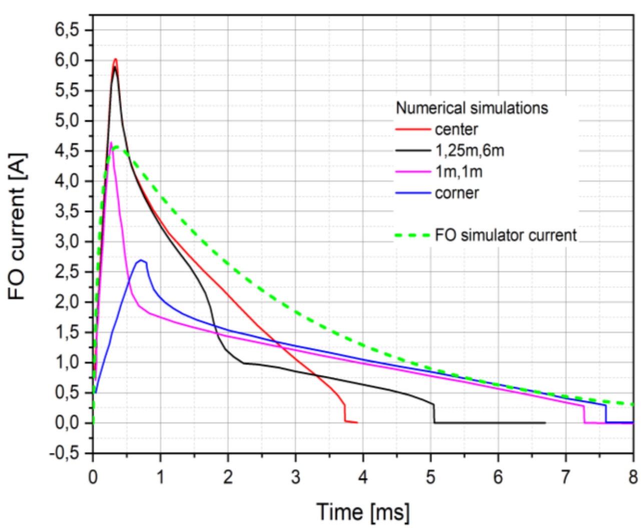
- Challenges: increase of electrical power onboard satellite

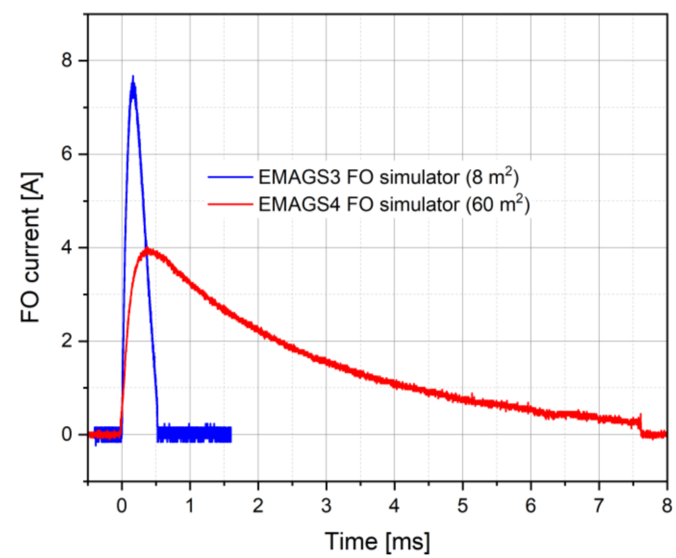
→ Larger solar array (>50 m²) = ESD lifetime?

→ More damages due to secondary arcing?

→ How to size representative primary plasma?

- Use of simulation codes (SoCCER/FOEBUS)
- FO Simulator adapted for ~5-7 ms lifetime ESD





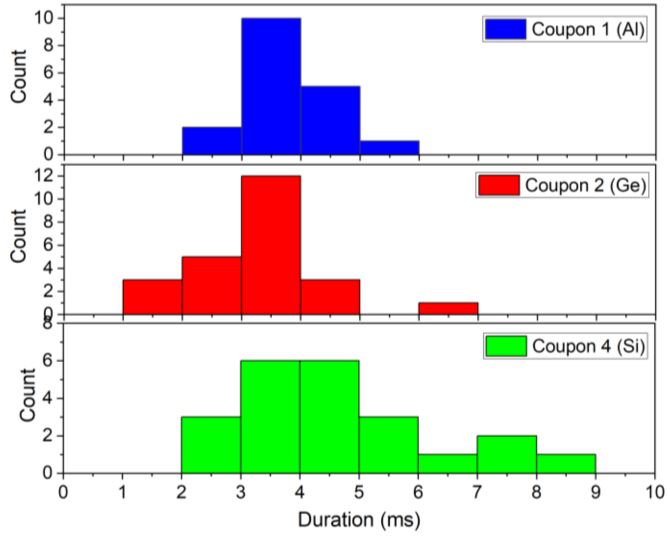
L. Monnin et al., J. Appl. Phys. 2021
P. Sarrailh et al., Proceedings of 17th SCTC, 2024

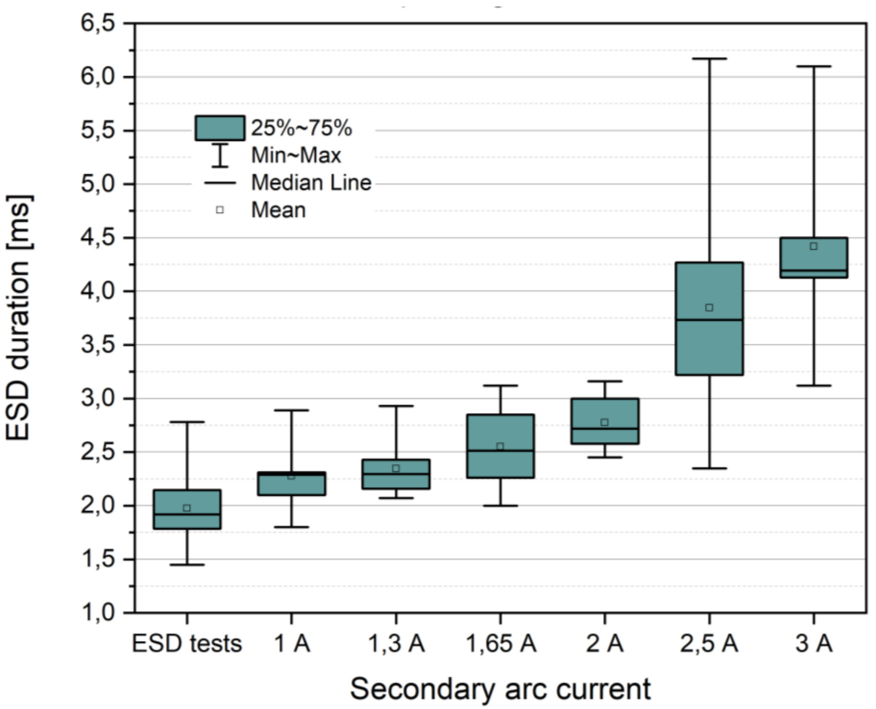
Evolution of ESD/arcing tests

- High dispersion of ESD duration when using « large SA » FO simulator

→ early extinction of cathode spot : instabilities when I < 2 A ?

- Coupling between primary discharge (ESD) and secondary arc



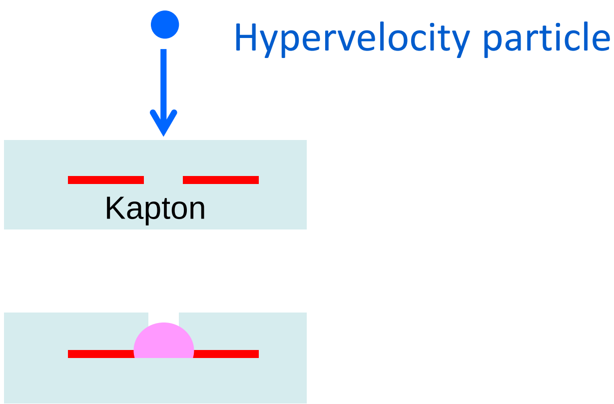


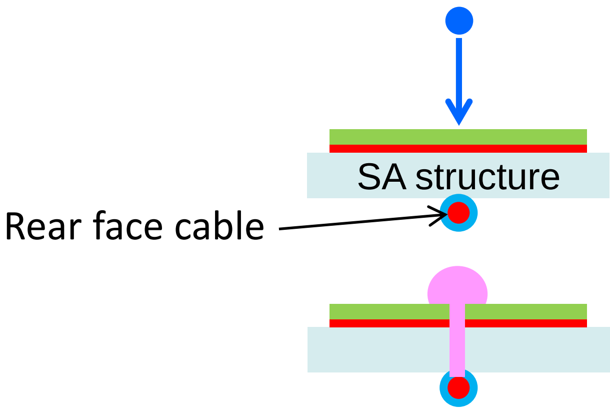
J. Jarrige et al., Proceedings of 17th SCTC, 2024

Perspectives: arc induced by MMOD impacts

Flexible solar arrays technologies: new situations for arcing

- Low thickness→ structure may be perforated by impact, small gap between power conductors
- Risk of arc on flexible harness (« flexprint »)





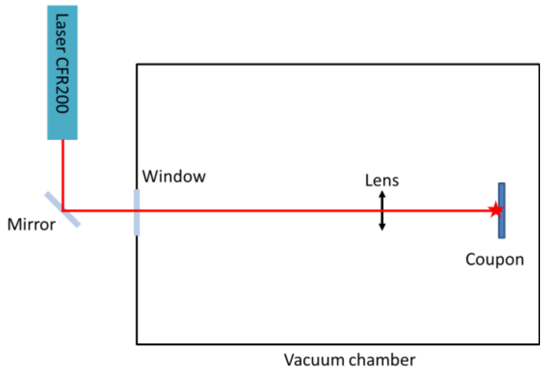
Perspectives: arc induced by MMOD impacts

- Simulation of the plasma produced par hypervelocity impact :

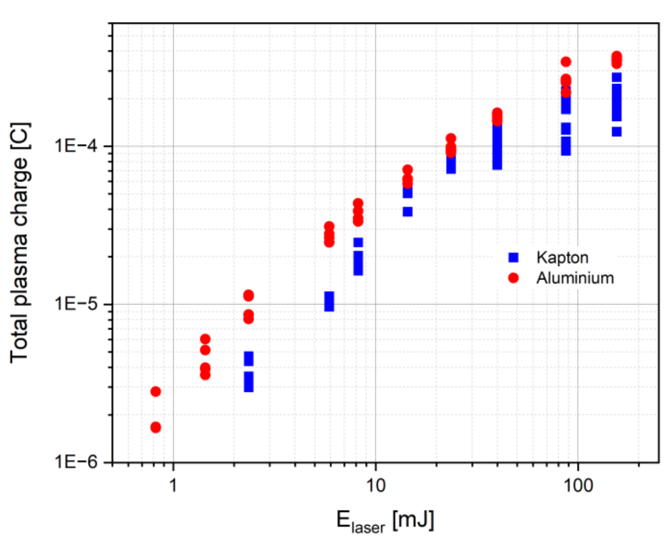
laser shot (Nd-YAG 1064 nm, 7 ns, 200 mJ)

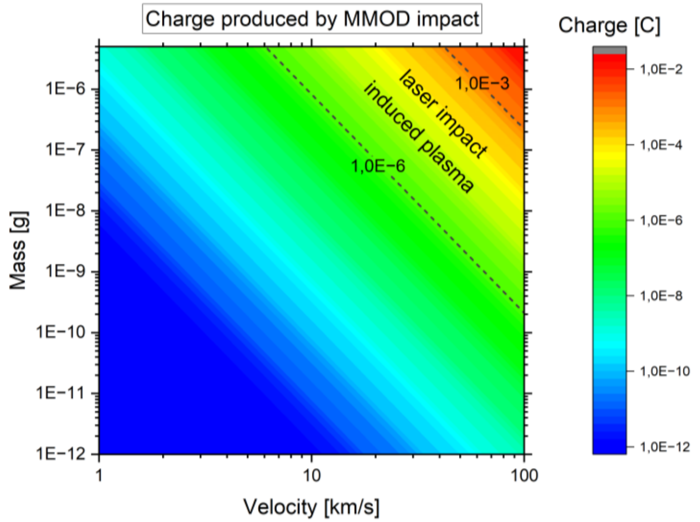
- Plasma characterization : triple probes

- Short duration primary plasma (~1 µs)



$$Q = 0.1m\left(\frac{m}{10^{-11}}\right)^{0.02}\left(\frac{V_m}{5}\right)^{3.48}$$



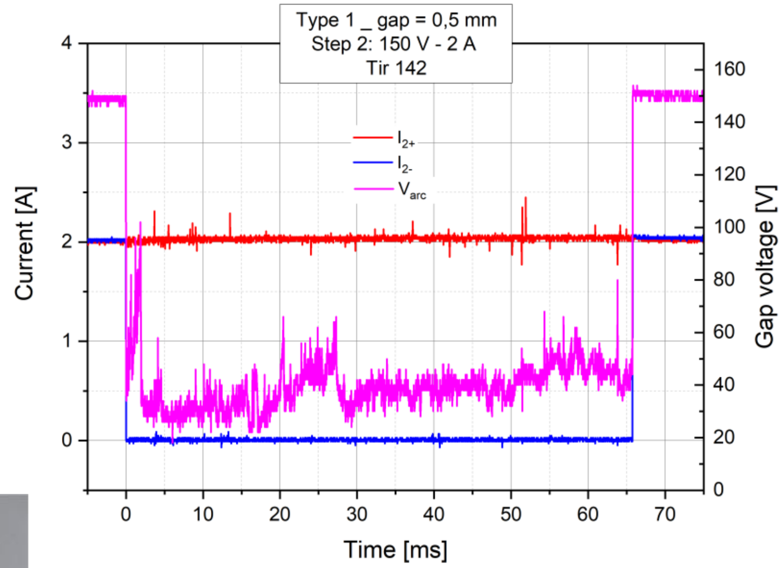


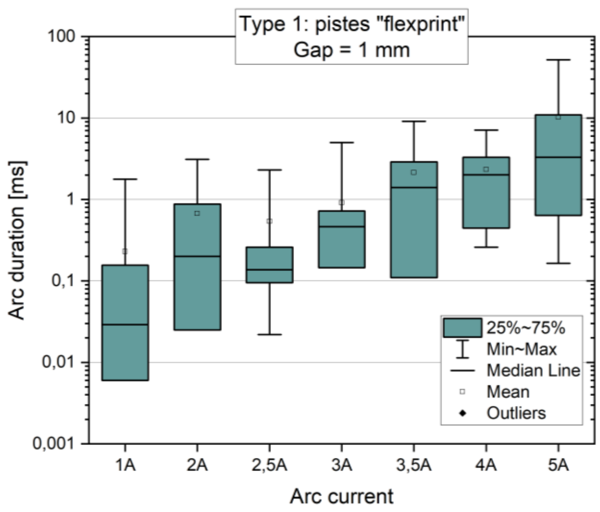
Perspectives: arc induced by MMOD impacts

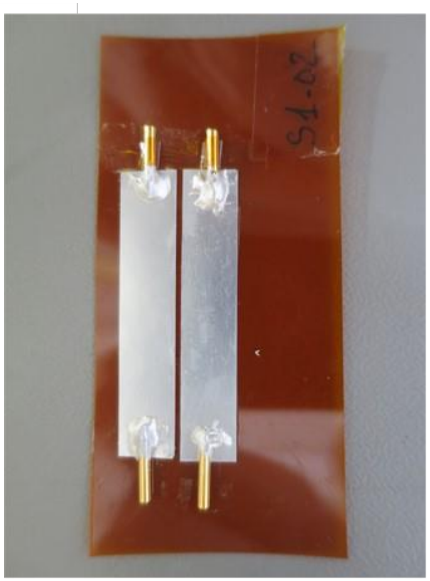
Arcs produced between tracks
(electrical circuit with SAS)

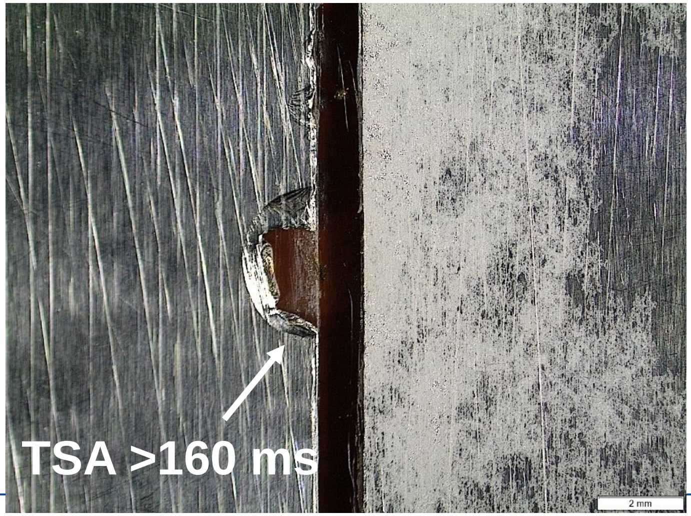
High dispersion of arc duration

Arc duration depends on current → reduction of instabilities ?







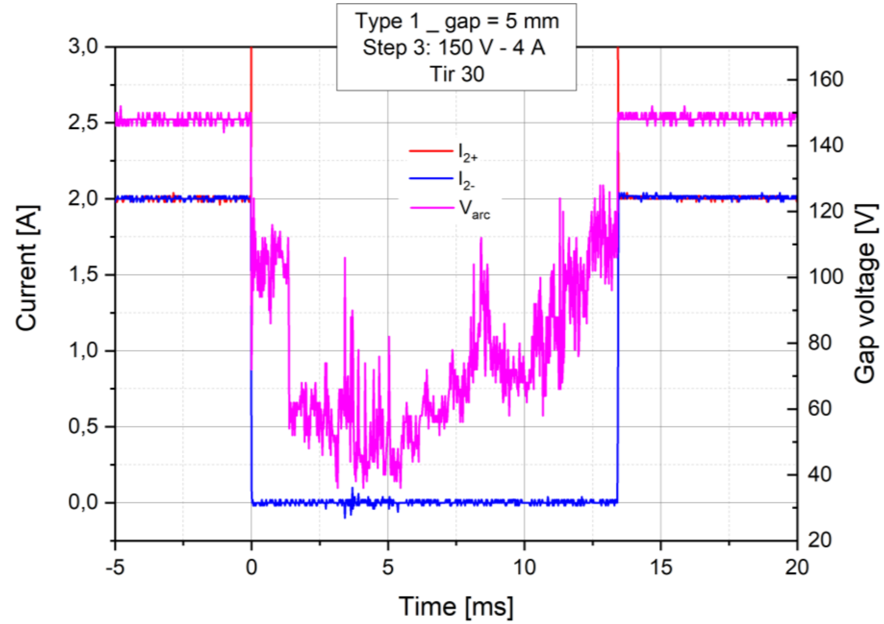


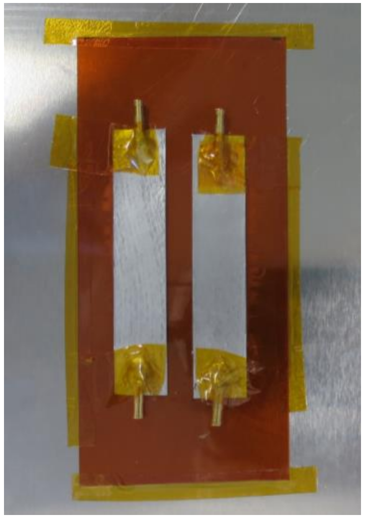
Perspectives: arc induced by I

Arcs produced between tracks

(gap = 5 mm)

Good correlation between plasma column length and arc voltage





Camera rapide 10 000 fps

Conclusions

- Characterization/qualification against arcing risk on solar arrays
  - Standardized test methods (ECSS)
  - Tests are expensive… but necessary for any modification of solar array

- Development of large area SA
  - Evolutions of methods relie on simulation codes
  - Probability of longest ESD → overtesting risk, lack of flight data
  - Existence of coupling between ESD cathode spot and secondary arc

- Understanding initiation and sustainment mechanisms of secondary arcs
  - Improvement of models & comparison with experiments
  - Spatial distribution of current
  - Advanced diagnostics : OES (T_e, n_e, LTE assessment)

C. Sol, "Simulation of electric arcs and discharge plasma on the solar panels of satellites", Wednesday 06/04 11:30

Acknowledgment

- EMAGS4 project (ELECTROSTATIC DISCHARGE MITIGATION OF EUROPEAN PHOTOVOLTAIC ASSEMBLIES)

- R&T no. R-S21/MT-0003-216: Arcs déclenchés par impact MMOD sur générateurs solaires souples