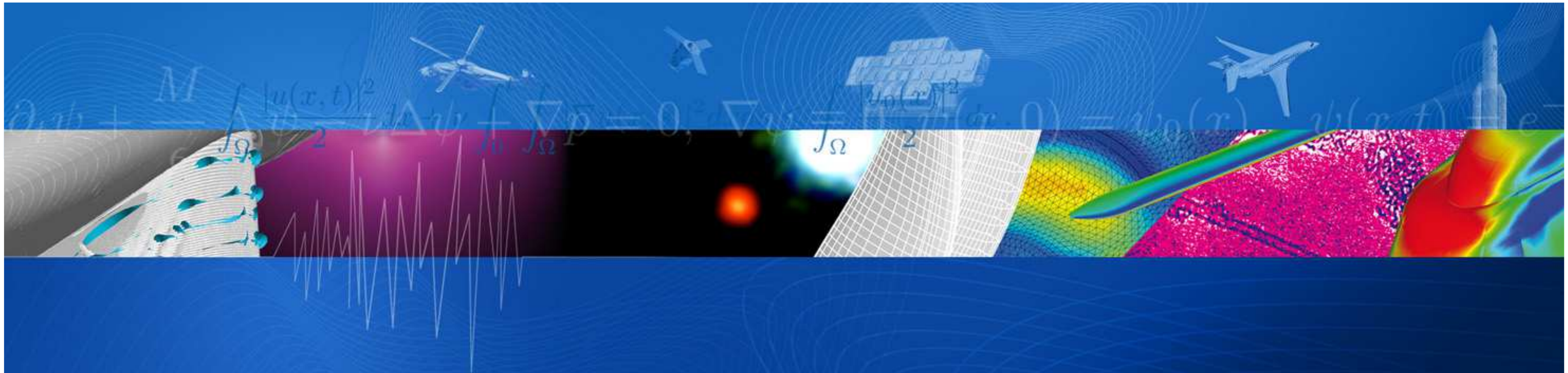

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Plasma current collection of high voltage solar array: numerical investigation

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Motivation and context

Solar panels are key but sensitive element of spacecraft.

In particular, they are composed of various materials with different electrical properties.

It leads to differential charging of the spacecraft surfaces and potentially to electrostatic discharges.

Because of the wide range of scales of the panel elements, it is difficult to model and solar panels involving new technology/layout requires experimental tests.

All configuration cannot be tested => interest for accurate simlations.

Motivation and context

The potential of the spacecraft are strongly dependent on the current collected by the large exposed surface of the solar arrays.

Current collection effect differs depending on the conductivity of the collecting material: dielectric (cover glass) vs conductive (structure). Small conductors (cell edges, interconnects) represent a small fraction of the surface and are usually neglected.

But small conductors may be strongly polarized: their effective collecting surface may be quite different from their geometrical surface, thus changing the current balance at the global (spacecraft) scale.

Must be taken into account to have realistic computation of the spacecraft potential, but cannot be resolved spatially.

Need for models of the current collection by small conductive elements.

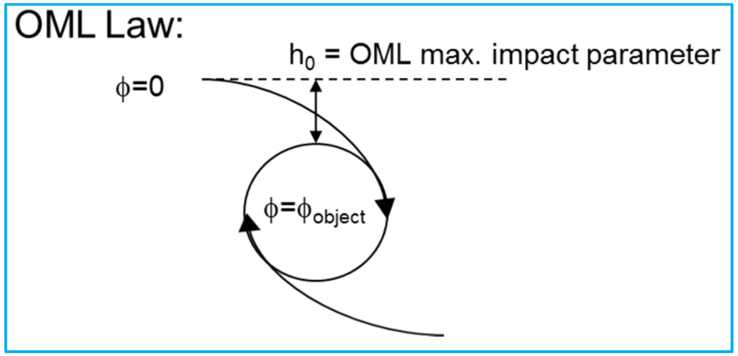
Previous work

Mandell and Katz (1983):

NASCAP-LEO, biased pinhole model (~ OML).

SPIS-GEO (2013):

OML (default) approximation



Limitations:

The simulation only split the unaffected total collected current towards conductor and dielectric: simulation of interconnects on an ITO cover panel has no effect.(even with 300V interconnects in a 0.1 eV plasma)

Only collected current, no emitted one (no snap-over)

Computation is averaged over the surface: impossible to identify what happen for a single (worst, typical,…) interconnect.

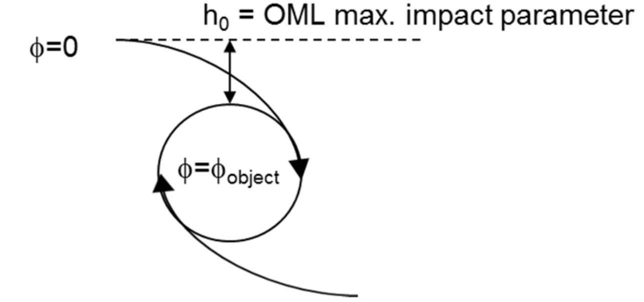
Panel current circuit is not simulated: no power loss computation…

Second order effects at the interconnects neglected (erosion, secondary currents,..)

Previous work

Mandell and Katz (1983):

NASCAP-LEO, biased pinhole model (~ OML).



SPIS-GEO (2013):

OML (default) approximation

Mandell et al. (2003):

current collected by a 2D strip:

$$j_{OML} = \frac{n}{2\pi kT} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} cos\theta \int_{\sqrt{-2q\varphi}}^{\infty} v^2 \exp\left(-\frac{\frac{v^2}{2} + q\varphi}{kT}\right) H(v,\theta) dv d\theta$$

$H(v,\theta)$ = 1 for open trajectories, =0 for closed ones.

$H(v,\theta)$=1 for all trajectories: exact solution but not accurate OML factor for a strip:

In reality the incidence angle is not conserved (non isotropic distribution on the collecting surface).

Mandel et al. 2003, use <H> determined from simulation, as well as empirical potentials in the gap determined from Gilbert simulations. Results OK but only suited for a particular solar cell geometry.

Modified OML law for plane 2D interconnects

Modified OML Law (acceptance angle):

OML: maximum impact parameter h_0. Effective collection surface multiplied by h_0/r.

Works for a cylinder in free space, particles arrive from all directions.

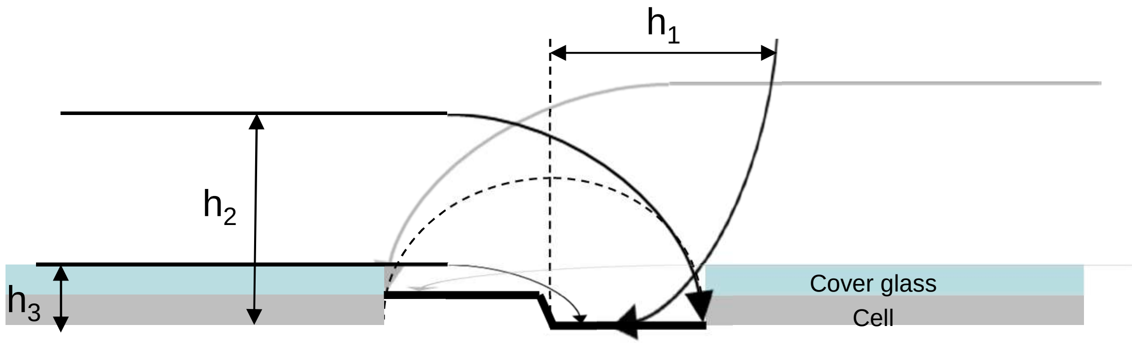
But for an interconnector on a solar panel, only some directions of arrival are possible.

The acceptance angle can be expressed as the following expression:

$$\Delta i = \Delta i_1 + \Delta i_2 + \Delta i_3 - \pi$$

$$\Delta i_{n=1-2} = \begin{cases} \operatorname{acos}\left(\dfrac{h-h_n}{h_0-h_n}\right); h_n < h < h_0 \\ \dfrac{\pi}{2}; 0 < h < h_n \end{cases} \qquad \Delta i_3 = \begin{cases} \dfrac{\pi}{2} - \operatorname{atan}\left(\dfrac{h_3-h}{h_0}\right); 0 < h < h_3 \\ \dfrac{\pi}{2}; h_3 < h < h_0 \end{cases}$$

$h_{n=1\text{-}2}$ / h_0 functions are sigmoid functions of $q\phi/mv^2$ with a vertex around $q\phi = mv^2$ determined using hyperbolic trajectories.



$$h_1/h_0 = \begin{cases} 1 & ; \quad q\phi \ll mv^2 \\ \dfrac{(1-\sin\Phi)}{2\cos\Phi} & ; \quad q\phi \gg mv^2 \end{cases}$$

$$h_2/h_0 = \begin{cases} 0 & ; \quad q\phi \ll mv^2 \\ 1 & ; \quad q\phi \gg mv^2 \end{cases}$$

$$h_3/h_0 = \tan\Phi$$

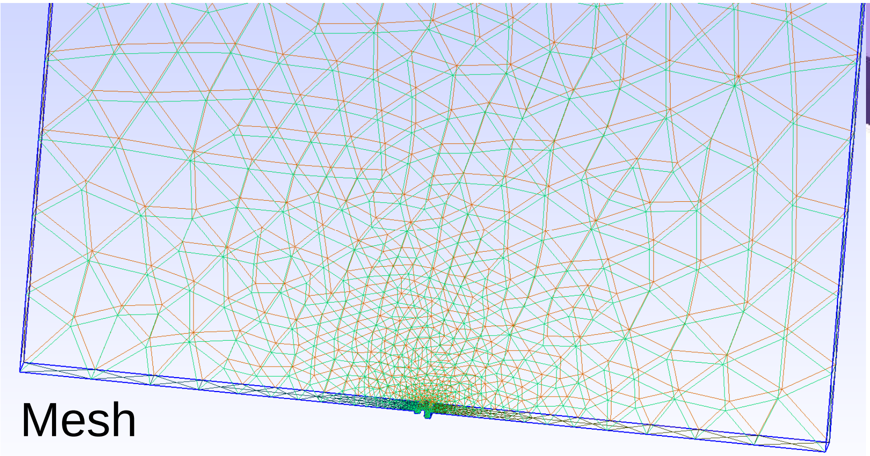
Simulations

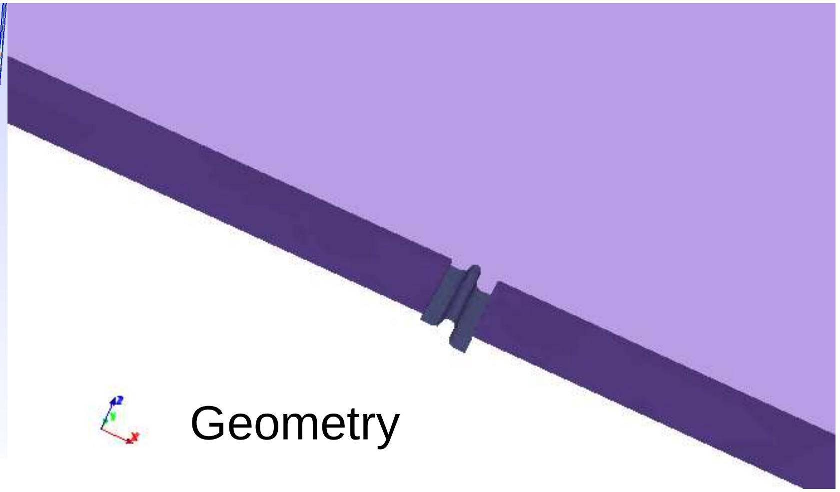
We perform simulation of the current collection by interconnects using SPIS (version DUST-5.1.8).

The simulation domain: 4 x 4 x 0.2 cm box.

Top face open to ionosphere plasma, sides reflective.

Bottom made of cover glass except for a 0.8 mm wide gap at the centre of the domain in which the metallic interconnect is located.





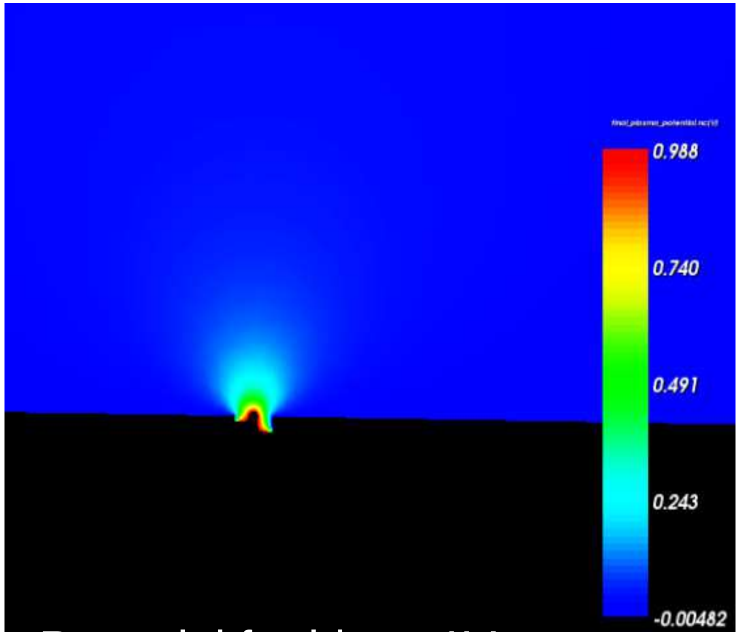
The ionosphere : $10^{10} m^{-3}$ 0.1eV Maxwellian electrons and ions at rest with respect to the solar panel.

Top boundary : potential fixed to 0V.

The cover glass : set to 0V, but may slightly evolve during the simulation.

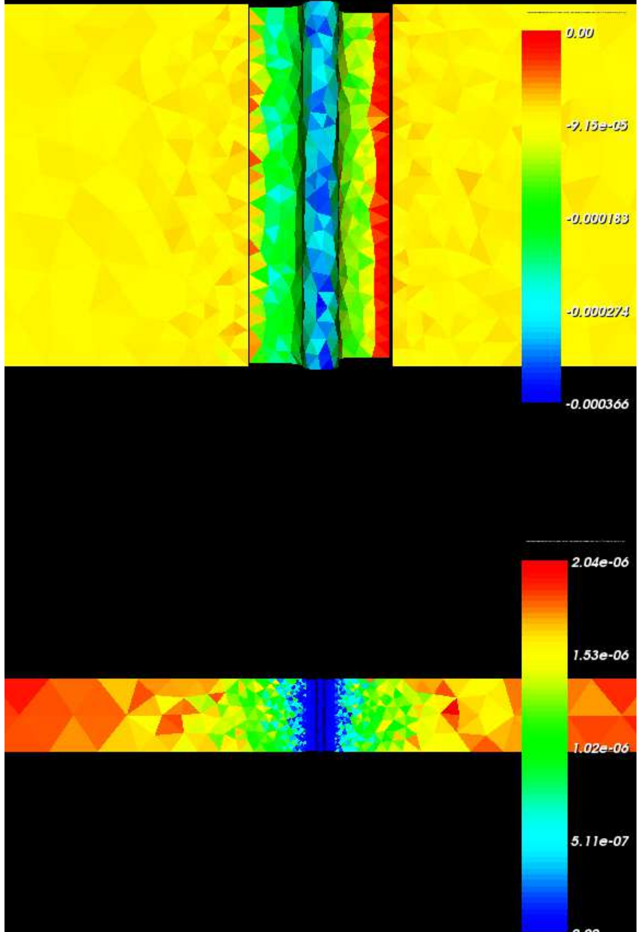
The potential of the interconnect evolves from -1V to 1V by steps of 0.1V.

Simulation results



Potential for bias +1V

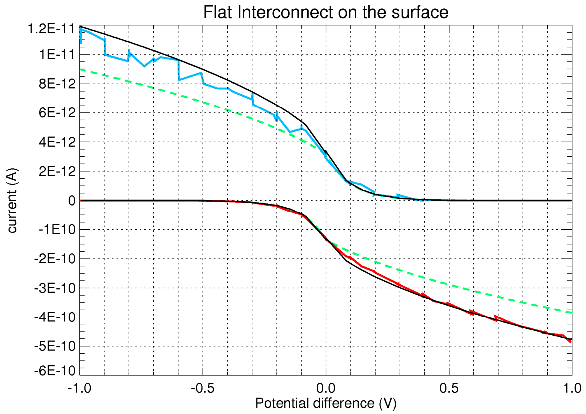
e- current (A/m²) +1V bias

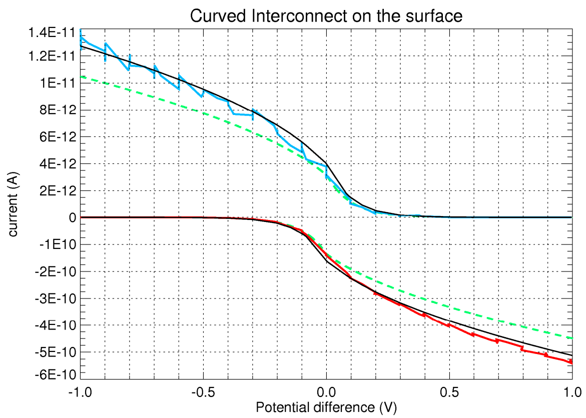


ion current (A/m²) +1V bias

Comparison model – Simulations I- Moderate Voltage

On the surface





Electron and ion currents collected by the interconnect.

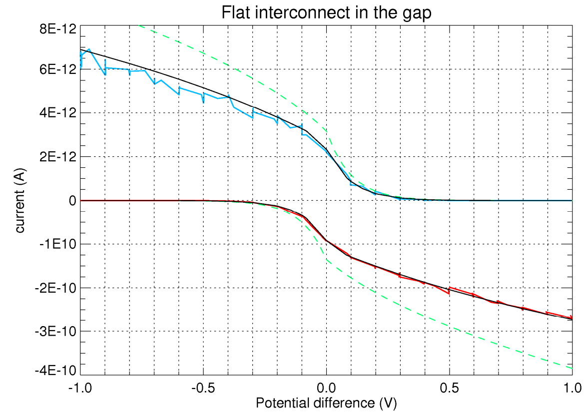
Black: model

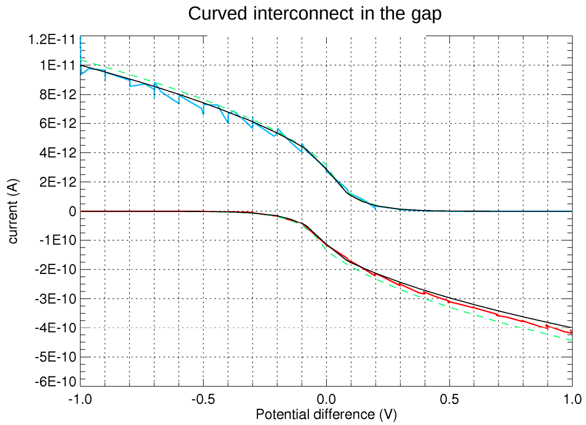
Green dashed: OML

Red: Simulation Electrons

Blue: Simulation H^+

Down the gap





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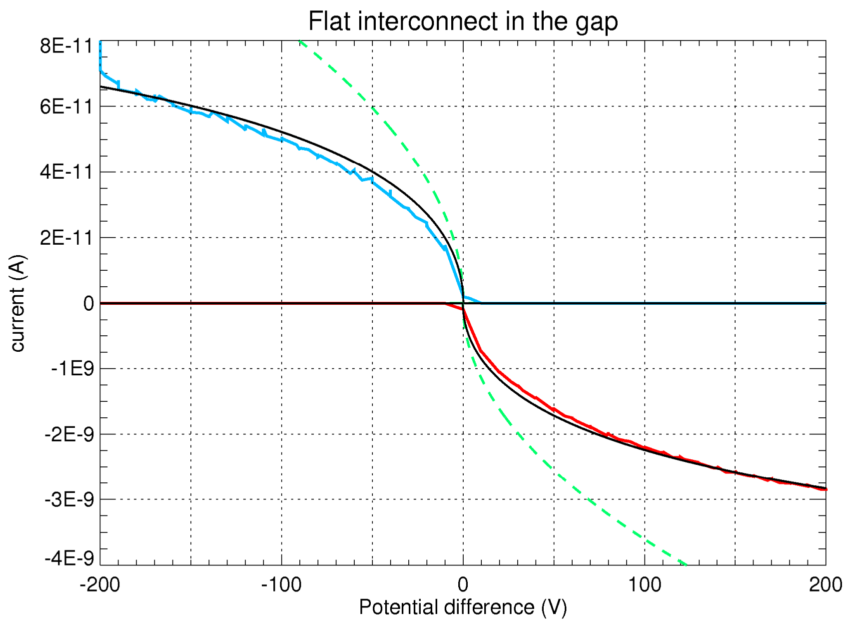
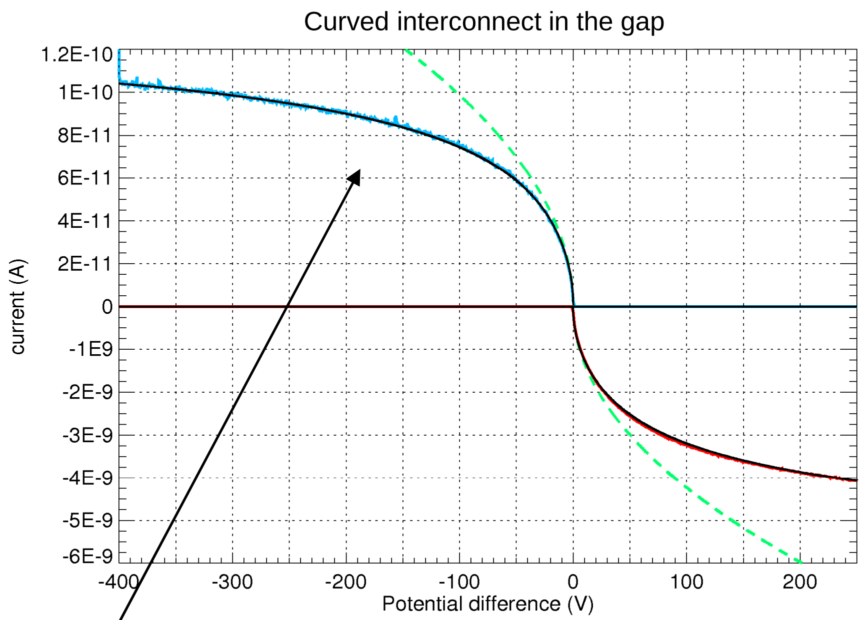
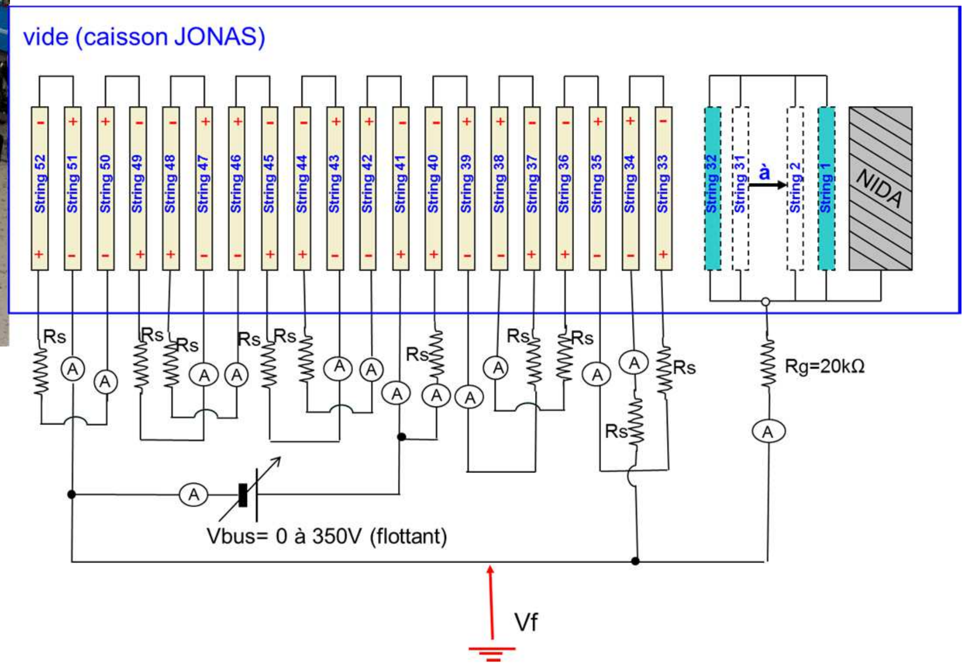
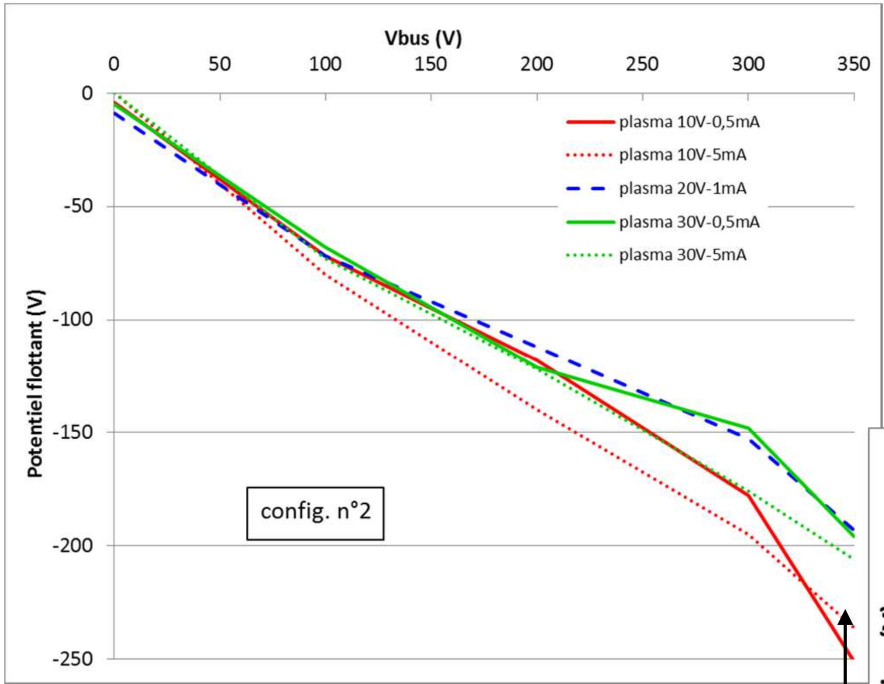




Current saturation due to finite cell surface

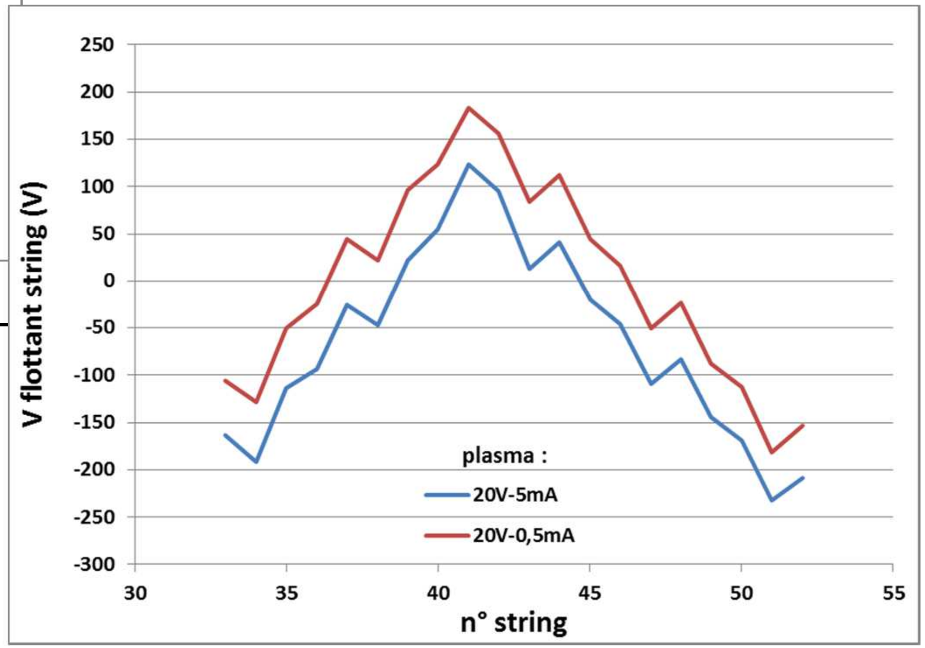
The model reproduces well the collected currents (including the recollection of secondaries, not shown). This analytic model can thus be implemented in SPIS to perform simulation at the panel/spacecraft scale.

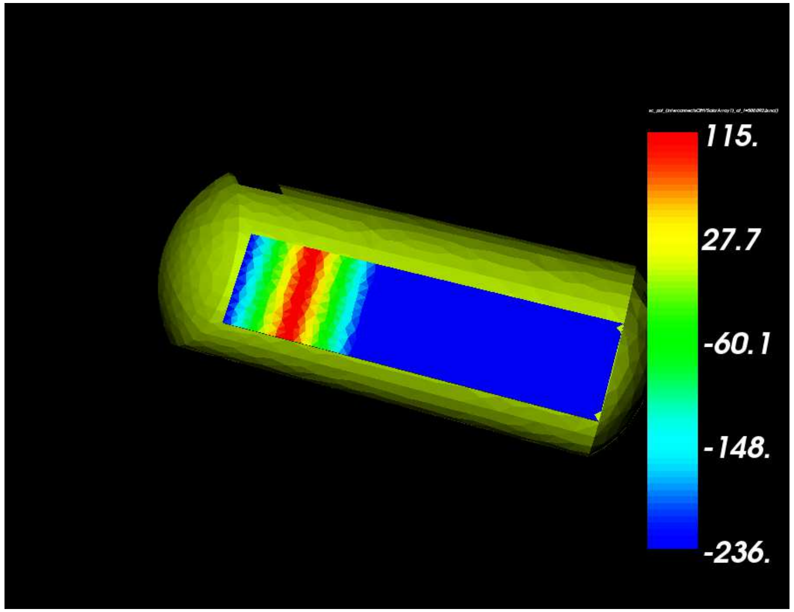

vide (caisson JONAS)
String 52
String 51
String 50
String 49
String 48
String 47
String 46
String 45
String 44
String 43
String 42
String 41
String 40
String 39
String 38
String 37
String 36
String 35
String 34
String 33
String 32
String 31
à
String 2
String 1
NIDA
Rs
Rg=20kΩ
Vbus= 0 à 350V (flottant)
Vf



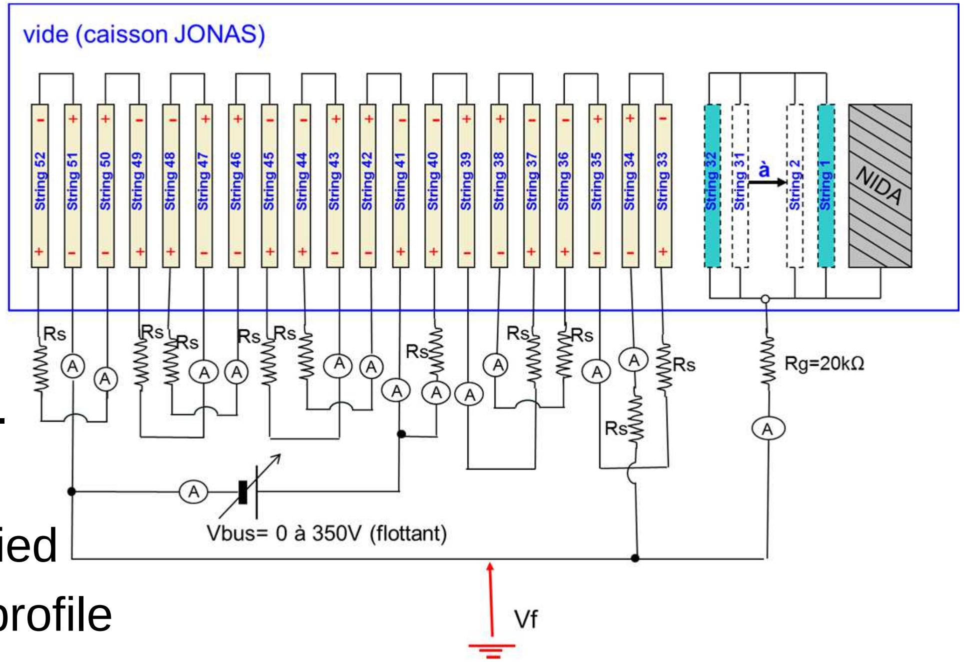
Interconnects represent <2% of the surface

But their polarity determines that of the whole panel.



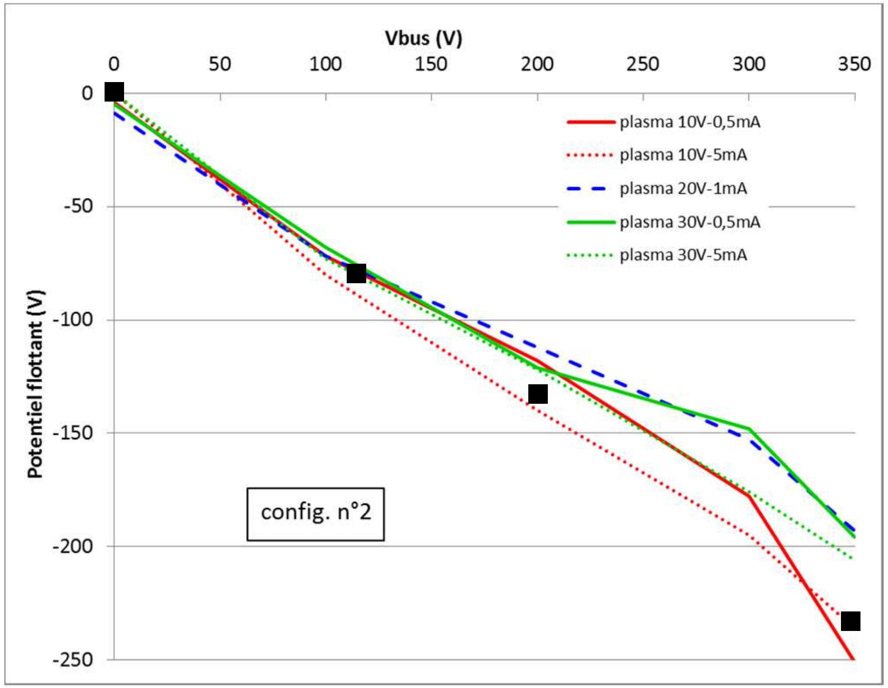


ONERA’s JONAS chamber is simulated with the solar panel inside. Environment is tuned to get as close as possible as JONAS one.



Impossible to reproduce the exact wiring of the strings in the experiment.

A constant potential difference is applied between strings so that the potential profile along the panel is close to that of the experimental one.



Interconnects represent <2% of the surface

But their polarity determines that of the whole panel.

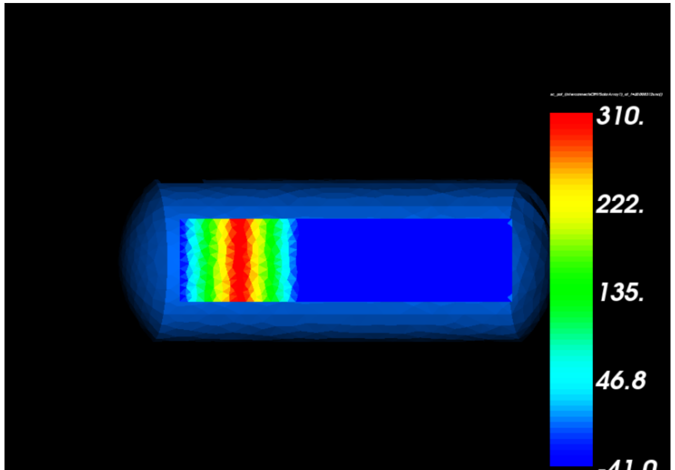
Simulations performed at various Vbus voltage with plasma ~20V and 2mA

Simulation with Vbus=350V. Initially the interconnects are all positive,

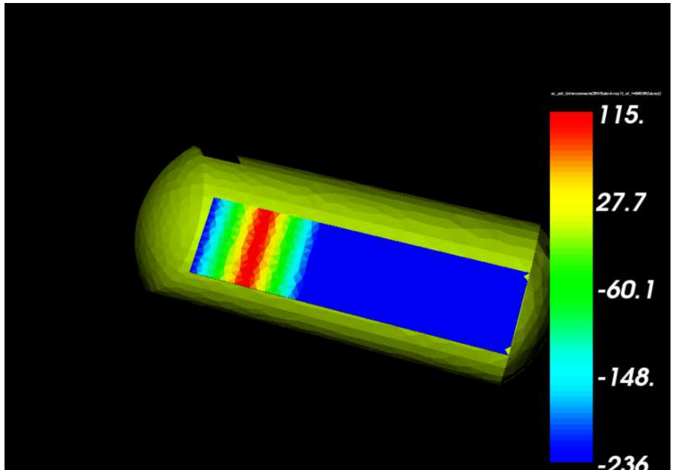
But the current they collect changes the whole solar panel potential to -240V

At the end, only a few strings have a positive potential.

The panel potential is almost only determined by the current balance on interconnects



Interconnect potentials t=40s



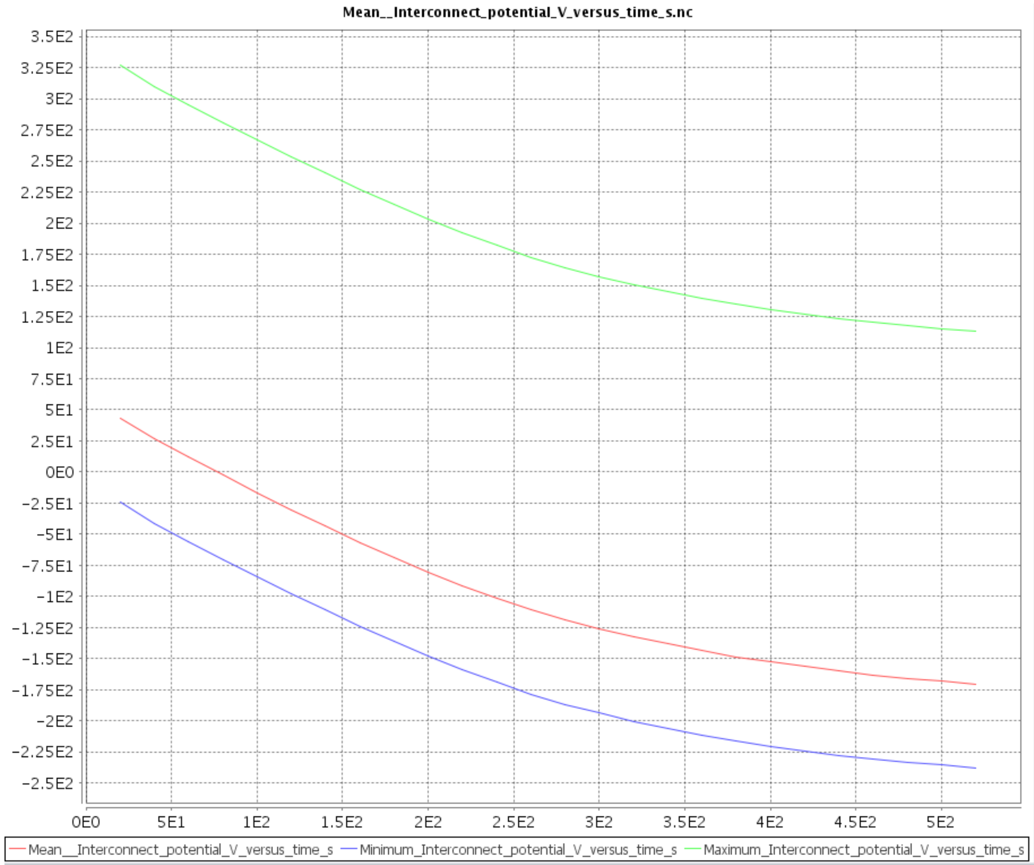
Interconnect potentials t=500s

Simulation with Vbus=350V. Initially the interconnects are all positive,

But the current they collect changes the whole solar panel potential to -240V

At the end, only a few strings have a positive potential.

The panel potential is almost only determined by the current balance on interconnects



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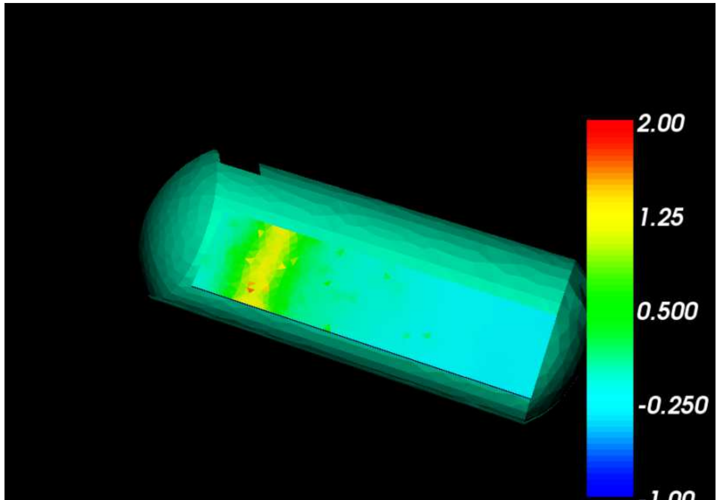
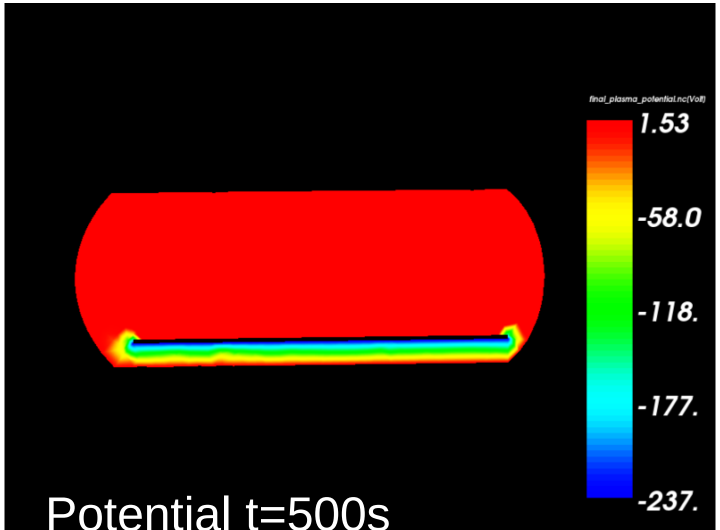
Simulation with Vbus =350V.

The effect of the interconnect polarization is visible on the cover glass surface potential. High positive potential interconnects tend to collect all electrons.



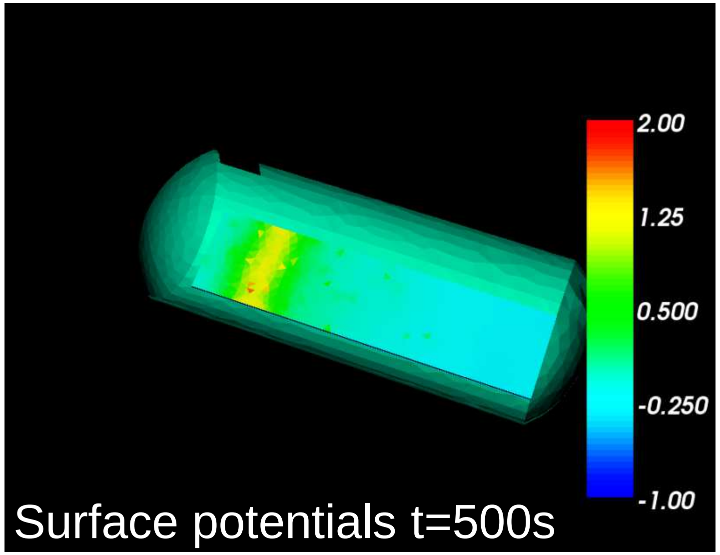
Surface potentials t=500s



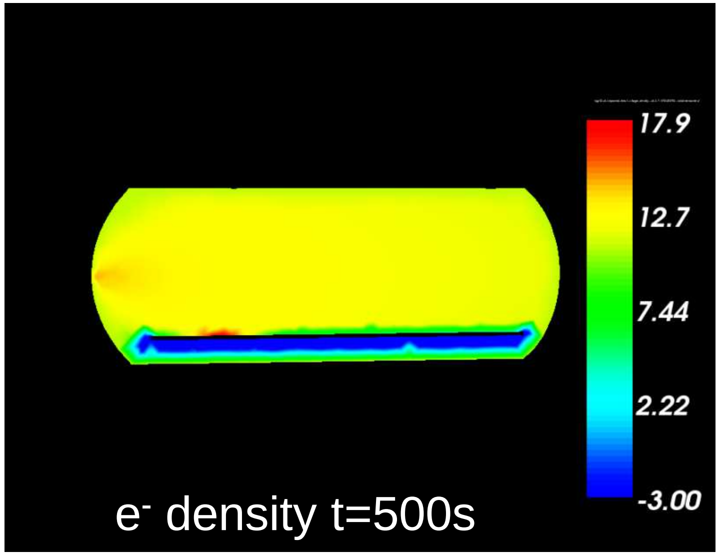
Potential t=500s

Simulation with Vbus =350V.

The effect of the interconnect polarization is visible on the cover glass surface potential. High positive potential interconnects tend to collect all electrons.



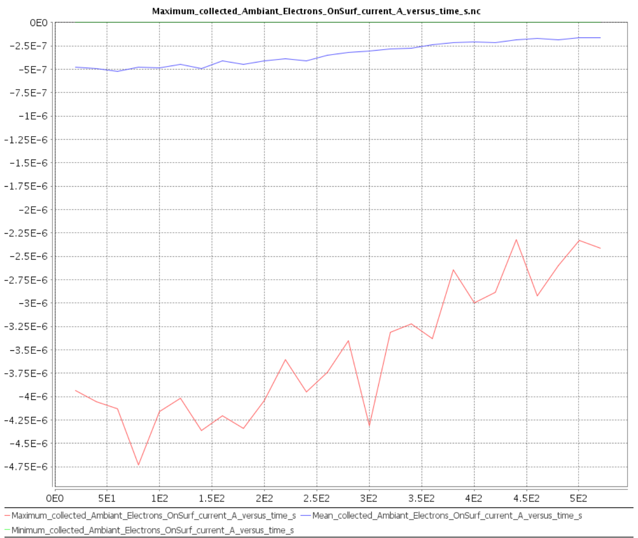
Surface potentials t=500s

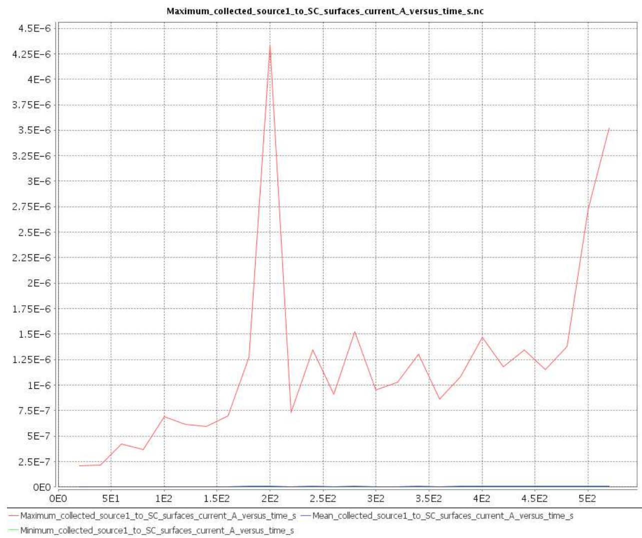


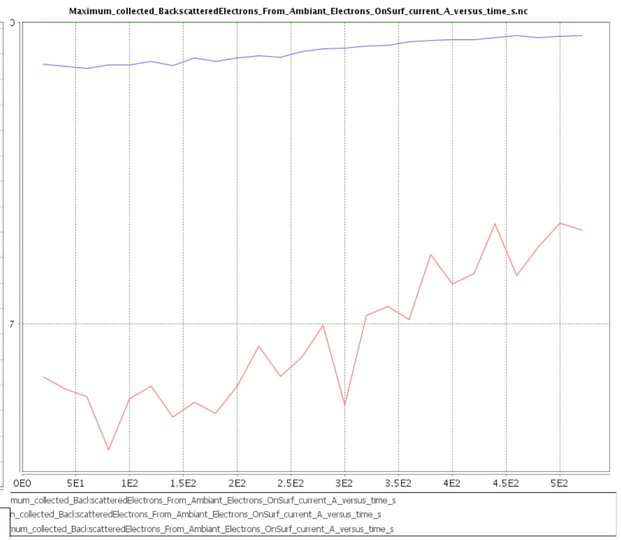
e^- density t=500s

Simulation with Vbus =350V.

The effect of the interconnect polarization is visible on the cover glass surface potential. High positive potential interconnects tend to collect all electrons.







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Perspectives (long term)

Ultimately, it would be desirable that SPIS be able to precisely compute the current collection by each unmeshed elements of the solar panel.

=> precise estimate of the power loss due to plasma recollection

including panel circuit solving, snap over effect,…

=> precise estimate of the electrostatic risks

ESD risk maps: identifies most probable ESD sites (interconnect, gaps)

possible full PIC "zoom" to better assess the risk (secondaries,...)

=> precise estimate of the erosion and ageing risks

better mapping of the eroding particle flux on each elements

better erosion models and aged material properties

ageing effect on solar cell circuit (coupling with ONERA McSOLAR code)

First step is done, but the road is long. A simplified, easy to use version of the present work should be implemented in the next version of SPIS (*ESA SPIS-EP contract*), but a full stable production version requires more effort.