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Measurement of the magnetic field and the shape effects on the plasma collection by a positive biased tether

Pierre Sarrailh, Jean-Michel Siguier, Gael Murat, Virginie Inguimbert, Jean-François Roussel

***Abstract*— BETs is a three-year Project financed by the Space Program of the European Commission, aimed at developing an efficient deorbit system that could be carried on board any future satellite launched into Low Earth Orbit. The previous measurements and simulations have permitted to show the effect of the orbital velocity on the current collection law. In this paper, new experiments of current collection by a tether are proposed in order to assess the effects of the magnetic field and considering a tape shape instead of a wire. The experiments show that the currents measured never exceed current density predicted by the OML theory. But, it has been shown that, in some case, to use the OML theory leads to a significant overestimation of the current collected. Thermal issues due to the current collection have been observed and quantified. A detailed estimation of the deviation measured in experiments will provide the margins to take in the system integration of the tether.**

Keywords*— magnetic field, electrodynamics tether, Plasma experiments

I. Introduction

BETs [1]–[3] is a three-year Project financed by the Space Program of the European Commission, aimed at developing an efficient deorbit system that could be carried on board any future satellite launched into Low Earth Orbit. The operational system involves a conductive tape-tether bare to establish anodic contact with the ambient plasma as giant Langmuir probe. A key point of the operational functioning of the tether is the efficiency of the current collection by the section of the tether positively biased in comparison to the plasma. The previous measurements and simulations have permitted to show the effect of the orbital velocity on the current collection law. For a cylindrical shape and at high potential, exceeding several thousand's times the electron temperature of the plasma, no significant deviations of the collected current were observed in comparison to the OML law [3]–[5]. In this paper, new experiments of current collection by a tether are proposed in order to assess the effects of the magnetic field and considering a tape shape instead of a wire [6]–[11].

II. Experimental setup

The experiments were performed in the JONAS plasma chamber at Onera. The JONAS facility is a $9m^3$ vacuum chamber equipped with a plasma source providing drifting plasma simulating Low Earth Orbit conditions (equivalent density and temperature of plasma plus a drifting velocity representing the orbital velocity). The Earth magnetic field can be neutralized inside the chamber by a system of coils around the chamber. It permits to do the experiments with a negligible magnetic field, with the Earth magnetic field or with about two times the Earth magnetic field (by reversing the current in the coils). The sample (i.e. the wire or the tape) is composed by a measurement section delimited on the both extremities by two segments constituting a guard. The whole sample is set inside the chamber and polarized up to +1000V with respect to the chamber walls and the neutralizer.

The purpose of this study is to assess the collected currents by the tether polarized in an ionospheric type plasma, with different magnetic fields (compensated and non-compensated) and for two orientations of the tether with respect to the drifting velocity (perpendicular and parallel). The bare tether sample is fixed vertically in the middle of the JONAS chamber (see Fig. 1 and Fig. 3). It is constituted of three parts. The central part 30cm length is the measurement section. This section is polarized and the collected current is measured. An upper and a lower parts 30cm length are the guard sections. The both sections are electrically connected and are polarized at the same voltage as the central part but the current is not measured. They are acting as guards simulating an infinite tether length for the central part. The central part of the sample is electrically insulated from the upper and lower part of the

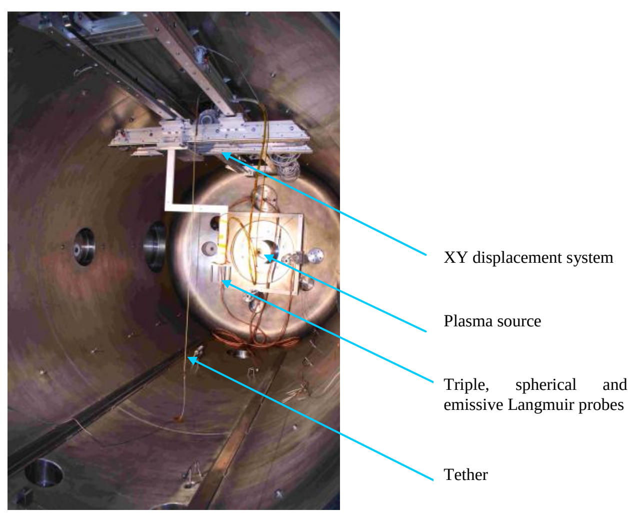

Fig. 1. Experimental setup for current collection measurement

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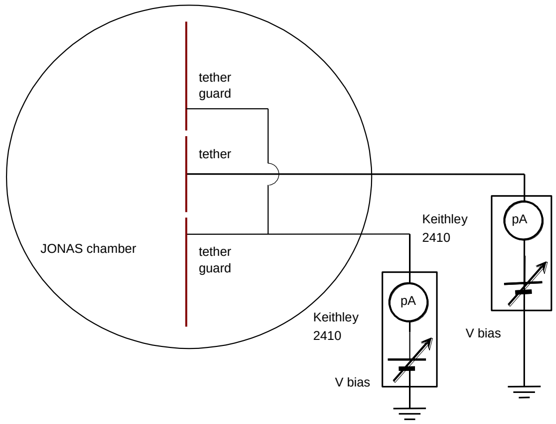


Fig. 3. Electrical circuit for current collection measurement

sample in order to separate the current collection on the different parts. The current measured on the central part is the only one that can be considered in a 2D situation. The upper and the lower part are subjected to end effects that do not permit to use these data in the real tether situation.

In the following results three samples have been used: a cylindrical sample and two tape shaped samples. The first tape shaped sample (called Sample 1) is a pure aluminum tape. The second sample (Sample 2) is multilayered material. It is an assembly of different tapes (polyester between two aluminum layers) stick by polyurethane glue. The sample is finally composed as follow: aluminum / PU glue / polyester / PU glue / aluminum. In a real situation the sample 2 is used for the highly biased sections that are collecting the current from the plasma and the Sample 2 are not polarized and used for mechanical constraint in the tether assembly. The both samples have exactly the same dimension.

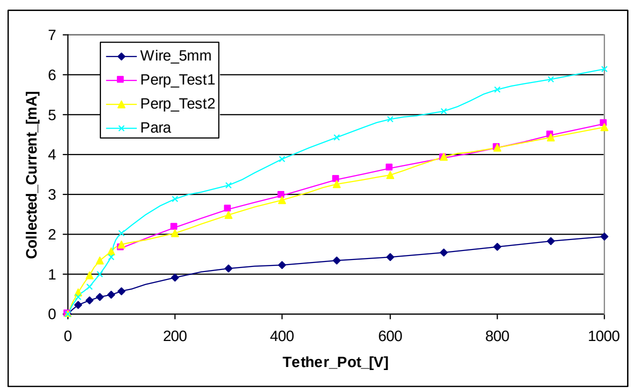
III. SHAPE EFFECT

The first question arising when we goes from the theoretical collection of a cylindrical sample to a real tether sample is the effect of the shape of the tether. In the following results, the current collected by different samples has been measured for a wire sample, a tape shaped sample oriented perpendicularly to the ion flux and a tape shaped sample parallel to the ion flux. The perpendicular orientation means that the tape surface is directly facing the flux (i.e. the cross section of the ion flux interception is maximum). The parallel orientation means that the flux is intercepted by the tape edge (i.e. the cross section of the ion flux interception is minimum). The plasma source current is 1mA and the biasing grid is polarized to -20V (i.e. 1mA current of Ar^+ ions with 20eV directed energy toward the samples). The ion flux is neutralized after the grid acceleration with a neutralizer injecting thermal electrons (i.e. with temperature of about 0.2 eV). The current collected by the sample has been measured for different polarization going from 0 to +1000V.

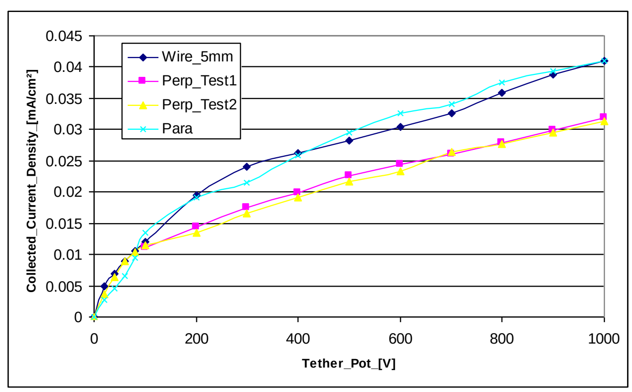
The current/tension characteristics are shown on Fig. 2a. On this figure, four measurement series are represented: one for the wire sample, two for the tape sample perpendicular to the ion flux (Test 1 with Sample 1 and Test 2 with Sample 2) and one for the tape sample parallel to the ion flux. The currents collected by the tape shaped samples are greater than the wire sample. It is due to the fact the collection surface area of the tape samples are greater than the wire sample. This figure also shows that, for a same tape sample, the current collected in the parallel case is lower than the perpendicular case at low potential (less than 80V) and greater at higher potential (greater than 80 V).

In order to compare to the cylindrical case, in the Fig. 2b, the measured currents have been normalized by the surface area of the samples in order to obtain a current density. As we can see on this figure, the maximum measured current density corresponds to the wire sample. In the cylindrical case, previous measurements [2] have shown that the measurements and the OML theory were in perfect agreement. It is thus logical that the current density collection never exceed the current collected by a cylindrical sample. At high potential (greater than 80V), the perpendicular case seems less efficient than the wire shape and the parallel sample. At low potential (less than 80V), the parallel case seems less efficient than the wire shape and the parallel sample.

In the perpendicular case, the current collection on the Sample 1 and the Sample 2 is the same. This means that the current collection is only dependent on the tether geometry. It was not so obvious result as the presence of an assembly can produce phenomena such like desorption susceptible to create a



a)



b)

Fig. 2. Tether collected current with 20V ions acceleration, 1mA plasma ion currents and with earth magnetic field compensation: a) total current collected and b) current density on the sample

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secondary plasma. But it is not the case in this condition. Nevertheless, the Sample 2 is more sensible to the heating to the current collection that will be discussed in Sections V and VI.

As a conclusion on the shape effects, the experiments show that the currents measured never exceed current density predicted by the OML theory. But, in some cases, the use of the OML theory leads to a significant overestimation of the current collected. This has to be considered in the margins to take in the system integration of the tether. In particular, it will be shown that the orientation of the tape tether in comparison to the ion flow can lead to a significant decrease of the current collection.

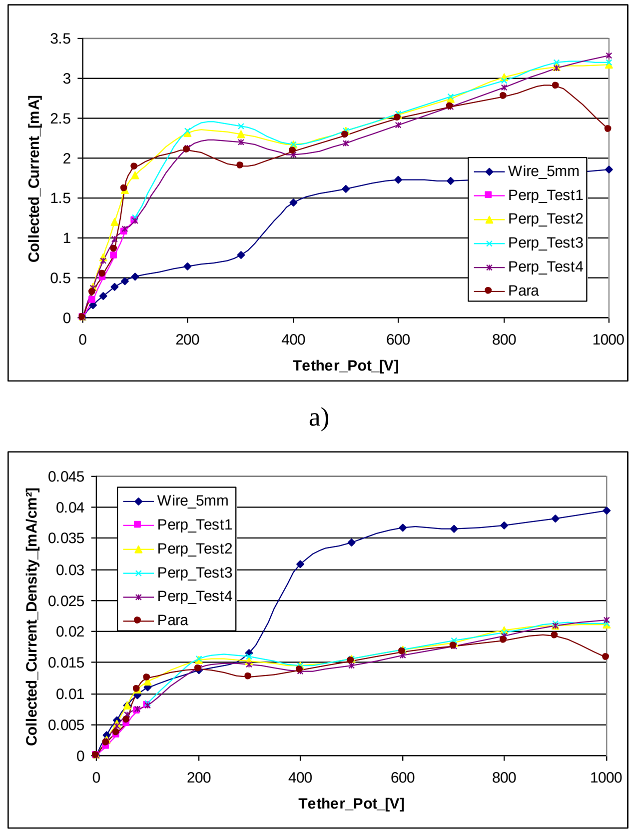
IV. MAGNETIC FIELD EFFECT

As electrodynamics tethers principle is based on the presence of a magnetic field (Lorentz force created by the orbital velocity of the spacecraft crossing the Earth magnetic field in LEO). The presence of the magnetic field has to be considered to assess the current collection. In the JONAS vacuum chamber, there is the opportunity to change the amplitude of the magnetic to obtain current measurement in different conditions.

In Fig. 5, the measurement of the current collection has been performed in the presence of the Earth magnetic field. These tests have been done in the same condition as in Fig. 2 at the exception of the magnetic field presence. In the results of Fig. 5a, four measurement series are represented: one for the wire sample, four for the tape sample perpendicular to the ion flux (Test1 and Test 2 with Sample 1 and Test 3 and Test 4 with Sample 2) and one for the tape sample parallel to the ion flux. It can be seen that the collected current is smaller due to the presence of the magnetic field whatever the shape of the sample. In order to compare the different shape, the current density is also plotted in Fig. 5b. The current density collected by the tape samples is about equal to the wire case for potential lower than 300 V and greater by more than a factor of 2 for potential greater than 400 V. It seems that for potential lower than 200V (approximately) the magnetic field does not affect the current collection. Between 200V and 400V, the current density in presence of the magnetic field decreases while the biasing potential increases. For potential greater than 400V, the current collected increases as a function of the potential increases but the current density collected by tape shaped samples becomes well smaller than the wire sample. There is also no significant effect of the tether orientation with respect to the ion flux. As in the previous cases, there is no difference on the current collection between sample 1 and sample 2. The only difference between the both samples is the thermal behavior.

V. THERMAL ISSUES

During the current collection measurement shown on Fig. 2 and Fig. 5, a degradation of the Sample 2 (multilayered tape shaped sample) has been observed. The degradation appears for a potential greater than +200 V at a plasma density of 2×10^{11} m^{-3} (plasma source 20V – 1 mA). The test with the Sample 2 and with magnetic field compensation has been



a)

b)

Fig. 5. Tether collected current with 20V ions acceleration, 1mA plasma ion currents and without earth magnetic field compensation: a) total current collected on the sample and b) current density on the sample

reproduced adding a thermocouple on the guard of the sample in order to estimate the temperature. In this experiment, the biasing potential is fixed to +200V. On Fig. 4, the temperature evolution on the sample guard can be observed as a function of the time. It can be seen that the temperature of the sample starts at t = 0 min from the room temperature. The temperature increases to reach a quasi-stationary state at a temperature of 66°C at t = 20 min. In such a case, the degradation is probably due to the melting of the PU glues layer that has a fusion

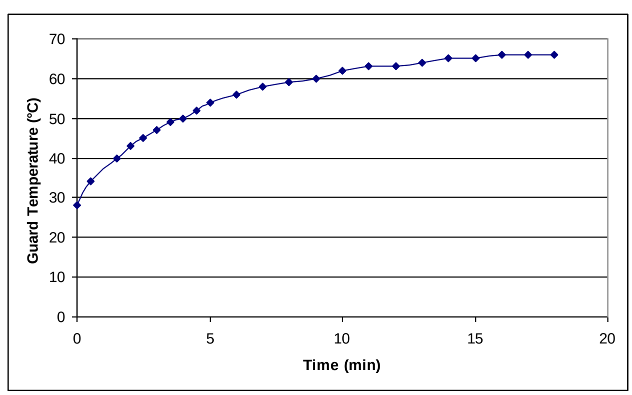


Fig. 4. Guard sample temperature after 20 min of current collection at +200V for a plasma source at 20V – 1mA.

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temperature of about +70°C.

We have also observed that the increase of the temperature is only due to the collection of energetic electrons because the sample temperature does not vary when there is no polarization of the sample. In order to understand this temperature increase, the energy balance on the sample can be written as the following expression:

$$2\times\varepsilon_S\sigma T_S^4 = 2\times J_e\times V_S + 2\times\varepsilon_S\sigma T_c^4 \qquad (1)$$

with ε_S the sample emissivity, σ the Stefan-Boltzmann constant, T_S the sample temperature, J_e the current density of electron, V_S the biasing potential, and T_c the vacuum chamber temperature. From the experiment, a current density of 0.0148 mA/cm² is measured for a potential of +200V. The heating source term due to the current collection is 5.92 mW/cm². It can be notice that for this plasma and this biasing potential, it is the same order of magnitude as the sun flux absorbed by the sample (about 20 mW/cm²). Taking as emissivity from the literature ε_S = 0.3, we found a sample temperature of 392 K (i.e. 119°C). This temperature is well higher than the measurement. Going in more detail on published emissivity of aluminum samples, a large range of emissivity has been found going from 0.02 for pure aluminum layer to 0.4 for oxidized aluminum. Performing emissivity measurement on the Sample 2, a permittivity of 0.085 was measured. Calculating the Sample temperature with this new permittivity, a temperature of 338 K (65 °C) is found. This calculation is in good agreement with the measurement of the temperature on the sample.

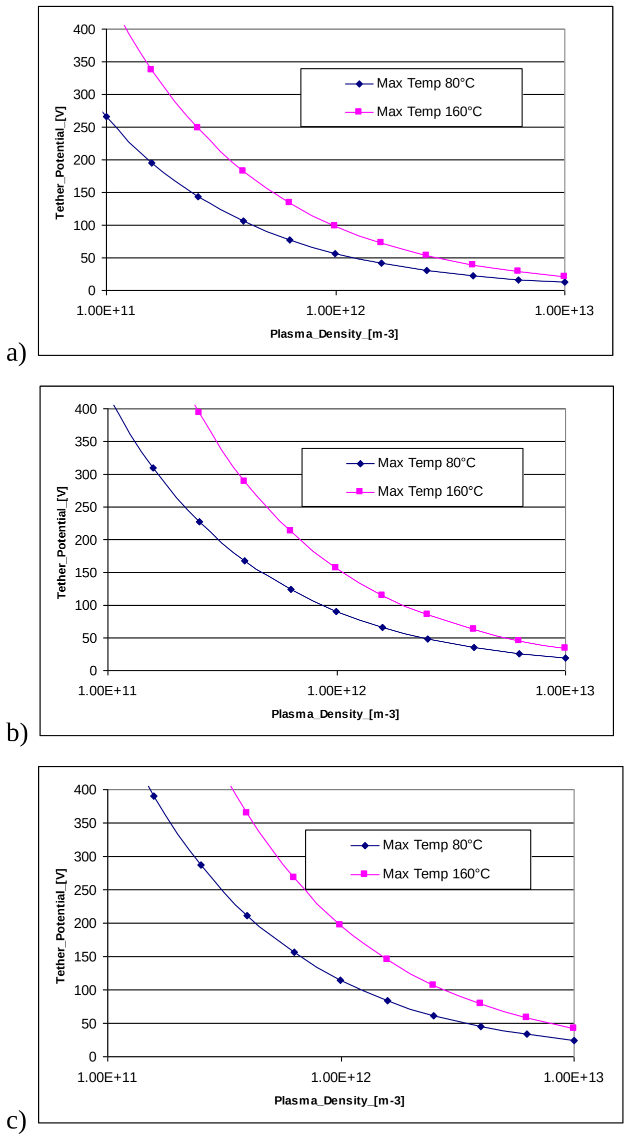

Fig. 6. Maximum operational tether potential as a function of the plasma density for a) $\varepsilon_S = 0.03$, b) $\varepsilon_S = 0.06$ and c) $\varepsilon_S = 0.085$

In this condition, the temperature appears just sufficient to melt the glue. This is contradictory with experimental observations: tether degradations after a few minutes of current collection. Different explanations can be proposed to explain the degradations. The first explanation is that the temperature is measured at the bottom of the tape sample, it is possible that the temperature is higher in the central part of the sample. The second one is that this temperature can be sufficient to vaporize the glue in vacuum that can produce a secondary plasma by ionization and by the way an increase of the current collection. The last explanation is that it is possible that the current collection is focalized on small parts of the tether due to the geometry at smaller scale. It can also be a combination of two effects creating a divergent process. For example, the melting of the glue can sensitively change the surface geometry of the sample (which is not planar at the end of the test). That can produce a local focalization on certain sections of the surface or a shading effect on other parts. That can increases the temperature locally.

From the experiments, we have seen that, due to the current collection, the multilayered sample (Sample 2) degradation occurs at a quite low temperature (~ 65°C). It could be due to local focalization of the current on a small part of the tether that locally increases the temperature. It is confirmed by the fact the tether does not melt uniformly but the melting seems to start at one position and extends in other directions from this initial point.

VI. Thermal Constraint for Tethers

From a simple calculation (eq. 1), this temperature increase has been simply explained by the current collection (i.e. kinetic energy deposition of the electrons in the material). This simple relation has been validated during experiments and can be used to define operational points of the tether where there are no thermal risks on multilayered samples. On Fig. 6, the equation 1 is used to define the functioning points (plasma density and local potential on tether) that permits to keep the temperature lower than 80°C (blue line) and 160°C (pink line). To simulate inflight operation, the chamber temperature is set to zero. On Fig. 6c, for an emissivity of 0.085, we see that the functioning points below the blue curve permits to have a tether temperature lower than 80°C. For the points between the blue and the pink curves, the tether temperature will be between 80°C and 160°C. For the points above the pink curve, the tether temperature will be greater than 160°C. For example, if we consider that the maximum plasma density during the mission will be 10^{12} m^{-3}, the maximum potential that the Sample 2 can support is 110V (for a temperature lower than

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80°C). If the maximum reachable density during the mission is 10^{13} m^{-3}, the constraint will be stronger and the maximum potential reachable will be +25V.

Of course, this constraint is material dependent. For glue supporting better the thermal constraint (with a higher fusion temperature for example), the maximum reachable potential is higher. For material with a higher emissivity (see Fig. 6a and Fig. 6b), the constraint will be smaller. For example, for a plasma density of 10^{12} m^{-3}, the temperature of the tether reaches 160°C at potential 100 V, 150V and 200 for permittivity respectively 0.03, 0.06 and 0.085.

Finally, it should be noticed that the sun irradiation is not taken into account in our calculation. It can contribute significantly to the thermal behavior but most of the time this constraint is taken into account during the design process of spacecraft. At the difference of the thermal balance with the sun flux, which mostly depends on the ration of the emissivity over absorbance of the material, the thermal contribution of the current collection does not depend on the material. There is no absorbance factor for the current collection (when the tether is positive, when it is negative, secondary emission should be taken into account). In this case, only the emissivity of the material is important.

VII. Conclusions

As a conclusion, the current collection without magnetic field is every time lower than the OML current. The OML theory thus overestimates the current collection. The OML theory remains a good approximation when the magnetic field is zero or very small (even if there is a small effect of the tether shape). In the case with the Earth magnetic field, the current collection is a factor of two smaller than the current predicted by the OML theory. The OML theory is also a good approximation taking in consideration the environment density are not known with this precision.

From the thermal point of view, melting occurs on the multilayered sample due to electron current collection. In order to have design margins, the sample 1 with pure aluminum is preferable where the positive potentials are high. We can notice that the most important parameter in thermal constraint assessment is the emissivity of the tether sample. Finally, the sun and albedo contributions in conjunction to the current collection should be carefully estimated to address the thermal behavior of the tether when multilayered technologies are used.

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