MODELING OF THE PLASMA THRUSTER IMPACT ON SPACECRAFT CHARGING

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Abstract

This paper presents the recent investigations done by the Research Department of Alcatel Space in the modelling of the electrostatic impact of plasma thruster on spacecraft charging. In particular, we will question the validity of the generally accepted hypothesis of Maxwell-Boltazmann distribution for the electron especially to take account of the plasma contactor effect.

In a first part, we will present the problem of the Maxwell-Boltazmann distribution to correctly model the spacecraft charging modification due to plasma thruster in the software SPARCS developed by Alcatel Space.

We will show that the plasma contactor effect of a plasma thruster is essential to estimate and model the electrostatic impact of the thruster. We will show too that the Maxwell–Boltzmann distribution for the electron is not adapted to model the current flow between spacecraft and GEO ambient plasma.

In a second part, we will present the plasma contactor principle and the physical mechanisms which generates charges exchange between spacecraft and ambient plasma. We will show that we can compare the physical mechanisms of the expansion of high-density plasma (the plasma generated by the thruster) into another plasma (the GEO ambient plasma) with the mechanism appearing in a PN junction. The region of high-density plasma is similar to the N region (electrons majority) of the junction and the region of low density is similar to the P region (electron minority). So, with this analogy we can understand how a current flow can circulate between the spacecraft and the ambient plasma through the plasma of the thruster. Finally, we will present a model for electrons to take account of this current flow and its impact on spacecraft charging.

Introduction

The always increasing of satellite on orbit life and mass make the Electric Propulsion Thruster more and more attractive for station keeping on geostationary telecommunication satellites. First developed by Russian researchers, the Stationary Plasma Thrusters (SPT) technology will be commonly used on commercial satellite in Europe in a nearest future. The Alcatel Space next satellite platforms will use SPT 100 for north-south station keeping. However, the introduction of an electric propulsion subsystem on our telecommunication satellite represents an innovation that requires to study their potential repercussion on the other systems of the satellite.

In a SPT thruster, the propellant (Xenon) atoms are ionised in a discharge chamber (anode). An electrostatic field is then used to accelerate the positive ions to produce the required thrust. To prevent the spacecraft from charging, the positive ion beam must be neutralised by an equivalent negative charge. In SPT 100 this electrons source is a hollow cathode. The plasma ejected by the SPT is then neutral, cold and very dense (about 10^{17} m^{-3} 30 cm away from thruster exit). Moreover a secondary plasma is created by charge exchange collisions between fast ions (primary ions) and slow neutral atoms. This relatively dense (about 10^{12} m^{-3}) low energy plasma can expand around spacecraft. These plasmas constitute charged particles store which can modify the natural environment, generate current due to the interaction between plasma and spacecraft and so modify the electrostatic charge of the spacecraft.

Spacecraft charging is considered as a phenomenon associated with the interactions between plasma and spacecraft surfaces. Charging effects can produce potential differences and high electrical field between spacecraft surfaces or between spacecraft surfaces and spacecraft ground. Above breakdown threshold, an electrostatic discharge (ESD) can occur. The transient phenomenon generated by this discharge may couple with spacecraft electronics (Electromagnetic Compatibility) and cause upsets ranging from logic switching to complete system failure. Discharges can also lead to degradation of exterior surface coatings and induce contamination of surfaces.

The charge and discharge phenomena due to the natural plasma in geostationary environment are studied for a long time. Methods and design rules have been set out to prevent from spacecraft charging and ESD occurrences in this environment. These design rules are mainly based on passive techniques of charge control like for example:

- The use of conductive surfaces connected to spacecraft ground.
- The careful selection of materials in terms of photoemission and secondary emission.
- The use of metallization and conductive coatings.

There are others spacecraft charging mitigation methods said actives methods. The principle of these methods is to eject a current. This active current source modifies the current balance equation and can control the spacecraft potential. When the potential of spacecraft is negative relative to the 0V of the surrounding plasma (typical case of the geostationary orbit), the objective of the active current source is to eject a current of electrons to bring the potential back to 0V. There are various methods to eject a current [1]. For example the sharp spikes method, see figure 1. Sharp spike protruding from charged surfaces generate very high electric field. At sufficiently high fields, field emission of electrons occurs reducing the negative potential of the conductive surfaces connected to the spike. Another method used the thermal emission, this is the hot filament emission method, see figure 1. The electrons are emitted from hot filaments.

These two methods are simple but their effectiveness is limited due to tips sputtering for example and electron guns are retained more effective [2]. An electron gun basically consists of a heated cathode and a series of collimating and accelerating electrodes (here referred as anode.

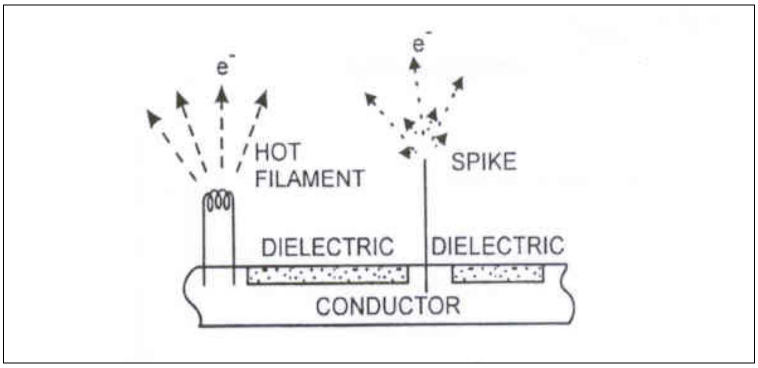

Figure 1. Electron emissions from a sharp spike and a hot filament

These methods based on electrons emission can be used only if the spacecraft is negatively charged. When the spacecraft is positively charged, ions emitters can be used [2]. But the inherent limitation of these devices based on charged particles emitters is that they can deal only with absolute charging situation. In case of differential charging, they can do nothing and the change in potential of only one part of the S/C could even trigger discharges between differently charged areas, thus worsening the situation.

The main interest of plasma source called plasma contactor to mitigate the spacecraft charging is that they can be employed to address charging situations of both signs and, more important, they can also alleviate differential charging problems. The principle of a plasma contactor is to emit a high-density and low temperature plasma. This plasma provides a conductive path between charged spacecraft and the ambient plasma environment. This is the same function as electrical grounding wire. The principle of a plasma thruster like SPT is precisely to generate a high-density and cold plasma. So, we can think that a plasma thruster will act more or less as a plasma contactor.

The software SPARCS (SPAcecRaft Charging Software) developed in the Research Department of Alcatel Space simulates the electrostatic impact of plasma thruster on the spacecraft charging in geostationary environment. In the development of SPARCS, we have seen that the plasma contactor effect of a plasma thruster is essential to correctly estimate and model its electrostatic impact on the spacecraft charging. But we will see that the generally accepted hypothesis of Maxwell-Boltazmann distribution for the electron with the neutrality assumption is not adapted to take account of the plasma contactor effect.

Problem of the Maxwell Boltzmann and Neutrality Hypothesis in SPARCS

SPARCS will be used to make the spacecraft charging analysis. It will be used to predict the surface potentials when spacecraft is submitted to both geostationary environment and plasma from the electric thruster [3]. Now we have the 2D axi-symetrical version and a first version of the 3D. The parallel version is under development. The magnetospheric plasma is assumed to be collisionless, low density and hot whereas the propulsion plasma is characterised by fast and slow ions. So the Vlasov equation is used to model the ions. For the SPT plasma electrons, in a first step the Maxwell-Boltzmann has been used. In fact this distribution is valid only close to the plume. The potential of the SPT plume (plasma potential) decreases away from spacecraft. The primary ion density decreases in n_0/r^2 and as we use the assumption of the neutrality $n_i=n_e$ in the plume, the electron density decreases too in n_0/r^2. With the Maxwell-Boltzmann distribution, we finally obtain that the potential decreases in ϕ_0-2log(r). So inside the plume where r is small, this is correct but outside the plume where $r \rightarrow \infty$, the potentials tends towards $-\infty$, which is not valid. In fact it is impossible to describe the electron distribution near the plume (cold electrons 1-2 eV, dense 10^{15} m^{-3}, potential reference –10kV-0V) and at infinity (hot electron 10 KeV, low density 10^6 m^{-3}, potential reference 0V) with a single Maxwell-Boltzmann equilibrium function. Moreover, there is a problem too on the results of the potentials of spacecraft surfaces. As we have seen, in the plasma thruster plume we have n_i=n_e with $n_e = n_{ref}$. Exp[(ϕ-ϕ_{ref})/KT_e] with ϕ_{ref} and n_{ref} at the thruster exit, see figure 2. Due to the thruster functioning, the potential ϕ_{ref} is referenced to the potential of the cathode ϕ_{crp} and ϕ_{crp} is referenced to the conductive parts ϕ_{pc} (spacecraft ground) so $\phi_{ref} = Vc + \phi_{pc}$.

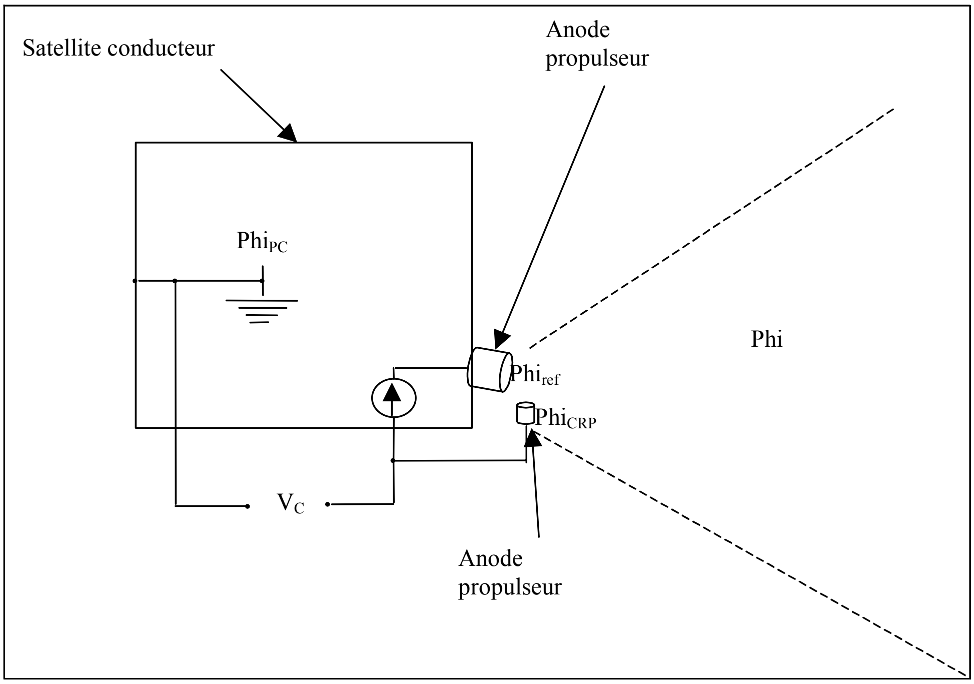

Figure 2. Configuration of potentials

Finally the current density can be written as $j_e = j_{ref}$.exp[(ϕ-Vc-ϕ_{pc})/KTe]. But on the spacecraft surfaces $\phi = \phi_{pc}$ and $j_e = j_{ref}$.exp[(-Vc)/KTe]. We see that the current is independent of ϕ_{pc} that is not realistic. Moreover, in these conditions the electronic current from the plasma plume is lower than the ion current. So, it is the electronic current from ambient geostationary plasma that balances this positive current. As the electronic current from GEO plasma is very low, the equilibrium potential is high (+40000V) that is not physical. So we can see that with the Maxwell-Boltzmann distribution and with the neutrality it is impossible to have good results. In fact, there is another relation between the plasma potential of the plume, the spacecraft potential and the magnetospheric potential which is impossible to model with the Maxwell-Boltzman distribution and neutrality. This relation is due to the plasma contactor effect of the plasma thruster. There is an electric circuit through the conductive path created by the plasma plume of the thruster. This circuit connects the spacecraft potential with the potential of the geostationary ambient plasma (0V). The plasma contactor effect is very important to determine the impact of the plasma thruster on spacecraft charging. Without this effect we could not explain the neutralisation of potentials observed in orbit. For example, in the case where the thruster is directly connected to the spacecraft ground, the spacecraft potential (ϕ_{pc}) is not directly modified by the particles of plasma thruster. The plasma potential of the plume is equal to the spacecraft potential, so the particles of the plume are not attracted by the potential of the spacecraft surfaces (grounding). The plasma is neutral and there is no net current so there is no modification of the spacecraft charge by the charged particles ejection. This is the plasma contactor effect due to the plasma conductivity that creates a conductive path between spacecraft and 0V magnetosphere. There is an electronic current flow from the spacecraft to the 0V that discharges the absolute potential of the spacecraft. Even when the thruster is electrically floating, the plasma contactor effect discharges indirectly the spacecraft potential. So in conclusion of this part, we see that the modelling of plasma contactor effect of the plasma thruster is essential but it is impossible with the Maxwell-Boltzman distribution and neutrality assumption.

Plasma Contactor Principle and Physical Mechanism

As we have seen before the plasma contactor principle is to create a conductive path between charged spacecraft and ambient plasma by the ejection of a high-density and low temperature plasma. In the case where the spacecraft is negatively charged for example, there is a electrons current flowing from spacecraft towards the ambient plasma through the plasma ejected by the plasma contactor, see figure 3.

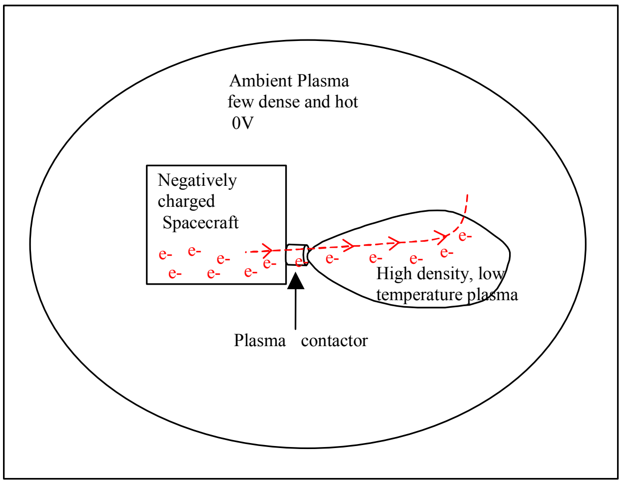

Figure 3. Plasma contactor principle

To model the plasma contactor effect it is necessary to understand the physical mechanism for current flow through the plasma plume. It can be illustrated with the examination of the no current flow case (no external perturbation).

The particles ejected by the plasma contactor (or the thruster) flow from regions of higher density to regions of lower density, this is the diffusion, see figure 4.

But the electrons move faster than the ions (due to ions high mass) and therefore reach the regions of lower density faster. This electrons flow leaves an excess of positive charge (see figure 4) and a electric field appears which retards electrons until there is no net electron flow [6]. A space charge region (a potential barrier) is created. The net force on the electron is zero: $F_e = F_d$. F_d is the diffusion force and at the equilibrium, D grad(n) = e.n.grad(V).

In fact, the physical mechanism of the expansion of high-density plasma into another plasma can be compared with the mechanism appearing in a PN junction, see figure 5.

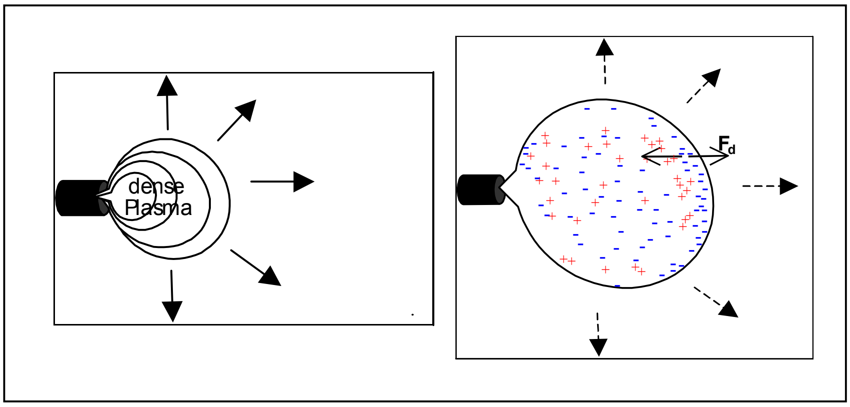

Figure 4.

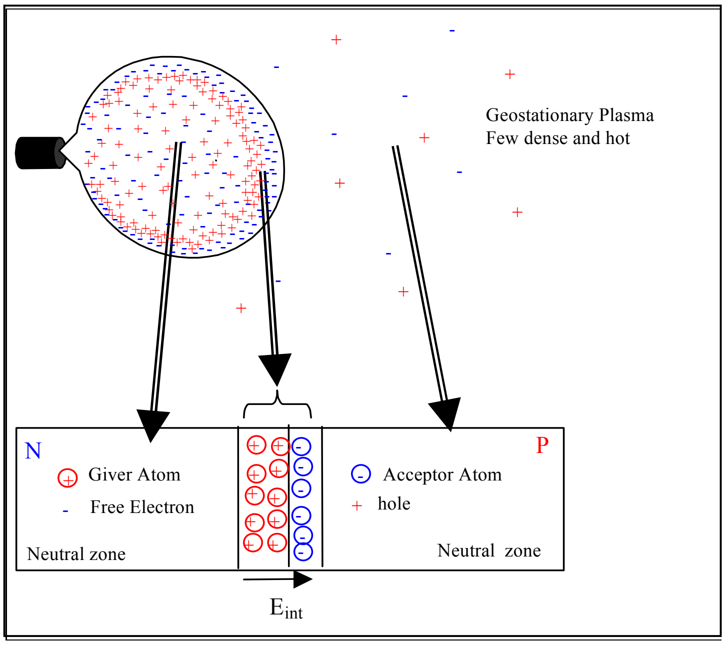

Figure 5. Analogy with PN junction

The region of high-density is similar to the N region of the junction and the region of low density is similar to the P region. At the junction, there is a space charge region created by the electrons diffusion from the N region where they are the majority carriers towards the P region where they are minority carriers. This current flow leaves an excess of positive charges in the N region and a negative charges in the P region. There is a space charge region and so a potential barrier.

Examine now the case where there is an external field. For the plasma contactor this external field is created by the difference between the potential of the plasma contactor (V_{ps}) and the potential of geostationary plasma (V_{pGEO}). For negatively charged spacecraft, the potential of plasma contactor (plasma thruster) is negative relative to GEO plasma (plasma contactor or thruster connected to spacecraft ground), so this corresponds to the forward biased in PN junction, see figure 6.

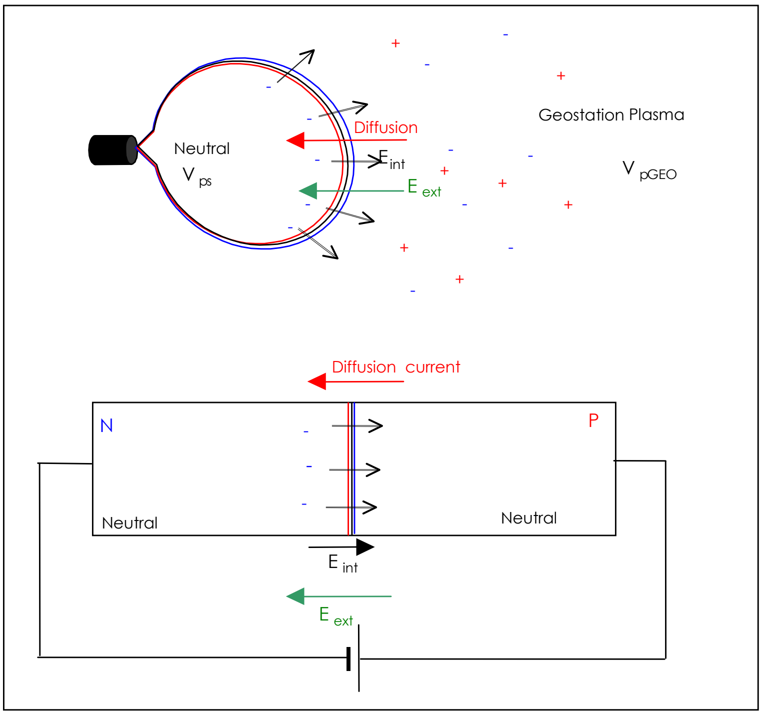

Figure 6. Forward bias

In these conditions, the external field E_{ext} reduces the internal field E_{int}(the potential barrier), and the electrons can diffuse from N region (from the dense region for the plasma contactor) to the P region (the GEO ambient plasma). So the electrons flow from spacecraft ground to ambient GEO plasma reducing the absolute floating potential of the spacecraft.
In the case of reverse bias, so when thruster potential is positive relative to GEO plasma, the external field is added to the internal field, see figure 7.

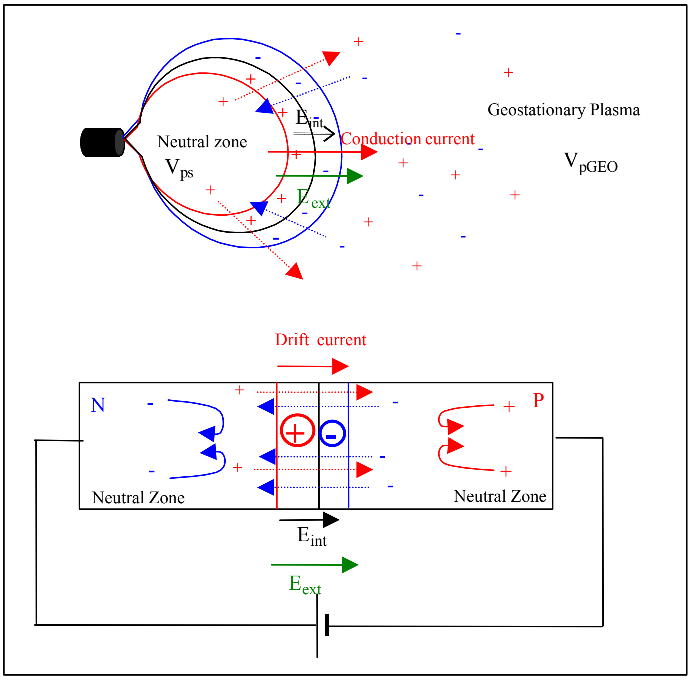

Figure 7. Reverse biased

The depletion region (space charge region) increases and the potential barrier grows. In the N region or dense plasma region, the electron have not enough energy to climb this barrier. The diffusion current becomes negligible. But the ions can flow from dense plasma to ambient plasma (GEO) and electrons of GEO plasma can flow towards the plasma source. This current is similar to minority carriers current (drift current) in the PN junction (electrons in the P regions and hole in the N region). The ions of the dense plasma are nearly motionless and the density of the electron in GEO plasma is very small so the drift current from GEO towards plasma source is small. The floating absolute potential of spacecraft is neutralise but more slowly than in the case of forward bias. When the field in the space charge region is very high, the electrons coming from GEO plasma gain sufficiently energy through the space charge region to ionise neutrals and the current rapidly grows. This is an avalanche phenomenon similar to the Zener effect in diode.

Finally, the phenomena of current circulation between spacecraft and GEO ambient plasma through plasma plume are similar to the ones appearing in a biased PN junction. If we compare the plasma contactor current/voltage characteristic measured with the diode characteristic, we can see that they are very similar, see figure 8 [4].

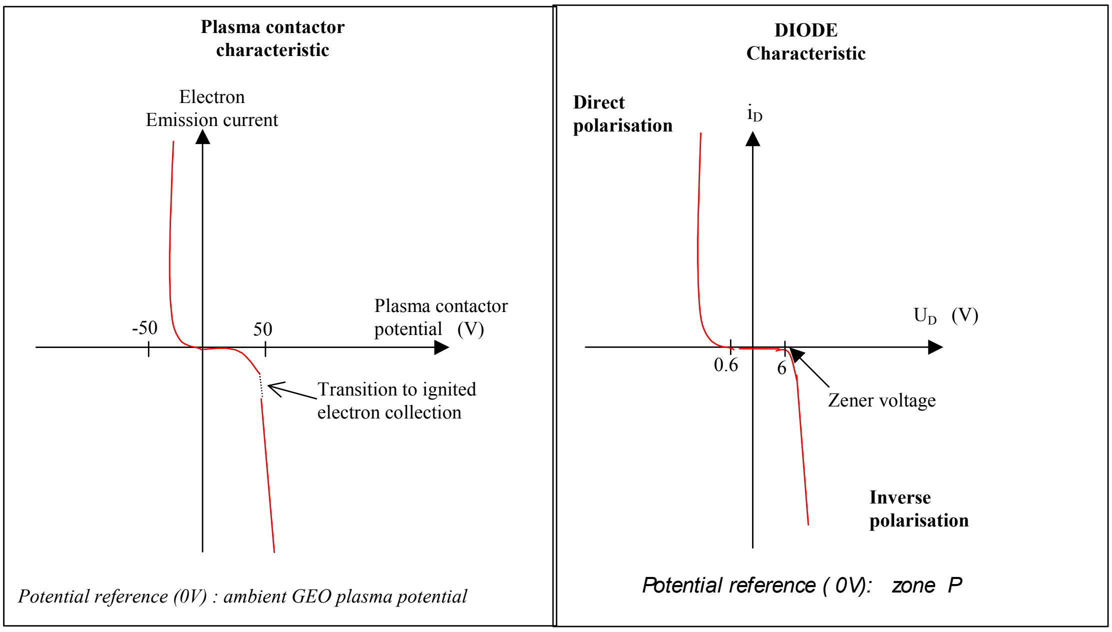

Figure 9. Diode and plasma contactor current/voltage characteristic

Plasma Contactor Modelling

We have seen that the Maxwell-Boltzmann distribution and neutrality model are not adapted to correctly model this current circulation We have seen too that the phenomena of current circulation between spacecraft and GEO ambient plasma through plasma plume are similar to the ones appearing in a biased PN junction.. So, this current for the plasma contactor can be calculated the same way as it is calculated in a biased junction.

So in a first step we will precisely calculate the current through a PN junction in function of the biased voltage.

In semiconductors, there are two kinds of current: the diffusion current and the drift current. So for holes and electrons, the total current density is:

$$J_p = q \cdot p \cdot \mu_p \cdot E - q \cdot D_p \cdot \frac{\partial p}{\partial x}$$

$J_n = q \cdot n \cdot \mu_n \cdot E + q \cdot D_n \cdot \frac{\partial n}{\partial x}$ with $\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = \frac{kT}{q}$ The constants D_p et D_n are the diffusion constants and μ_p and μ_n are the mobility.

In the case of the no biased junction, at the equilibrium, there is no net current. The diffusion current exactly balances the drift current. So for the hole for example, we have:

$J_p = q \cdot p \cdot \mu_p \cdot E - q \cdot D_p \cdot \frac{\partial p}{\partial x} = 0$ so $\frac{kT}{q}\frac{\partial p}{\partial x} = p \cdot E$ with E=-dV/dx.

With the boundary conditions we can write that $\ln \frac{p_{n0}}{p_{p0}} = -q\frac{V_0}{kT}$

In the notation used, « n » and « p » are respectively the electrons and holes concentration, the index « n » and « p » show the region where this concentration is measured, and finally the index « 0 » shows a concentration at the equilibrium.

So, the potential barrier is $V_0 = \frac{kT}{q} \cdot \ln \frac{N_a N_d}{n_i^2}$ with N_a and N_d the doping concentration in the P region and in the N region respectively.

With forward external bias, the potential of the P region is positive relative to the region N.

In this case $n_p = n_{p0} \cdot \exp(\frac{qV}{kT})$ and $p_n = p_{n0} \cdot \exp(\frac{qV}{kT})$, V is the bias voltage.

At the quasineutral N region input ($x=x_n$), in stationary state and in assuming there is no carrier generation, the continuity equation gives for holes:

$-U_p - \frac{1}{q} div \vec{J}_p = 0$ with $U_p = \frac{p_n - p_{n0}}{\tau_p}$, τ_P is the hole lifetime and $L_p = \sqrt{D_p \cdot \tau_p}$ is the diffusion length. At this point (neutral zone) we have only a diffusion current:

$J_p = -q \cdot D_p \cdot \frac{\partial p_n}{\partial x}$ and finally we have $-\frac{p_n - p_{n0}}{\tau_p} - \frac{1}{q} \cdot \frac{\partial}{\partial x}(-q \cdot D_p \frac{\partial p_n}{\partial x}) = 0$.

The solution of the differential equation with the boundary conditions is

$$p_n(x) = p_{n0}\left[(\exp(\frac{qV}{kT}) - 1) \cdot \exp(-\frac{x - x_n}{L_p}) + 1\right].$$

So J_p can be calculated : $J_p(x) = q \cdot \frac{D_p}{L_p} \cdot p_{n0} \cdot (\exp(\frac{qV}{kT}) - 1) \cdot \exp(-\frac{x - x_n}{L_p})$.

We can make the same for electrons in the P region, and we have:

$$J_n(x) = q \cdot \frac{D_n}{L_n} \cdot n_{p0} \cdot (\exp(\frac{qV}{kT}) - 1) \cdot \exp(\frac{x + x_p}{L_n})$$

In stationary state, the total current $J = J_p(x) + J_n(x)$ is constant in x. The recombination in the space charge region is assuming negligible.

$$J = J_n(-x_p) + J_p(x_n) = (q \cdot \frac{D_n}{L_n} \cdot n_{p0} + q \cdot \frac{D_p}{L_p} \cdot p_{n0}) \cdot [\exp(\frac{qV}{kT}) - 1]$$

that is often written as $J = J_s \cdot [\exp(\frac{qV}{kT}) - 1]$. This is the well-known expression of the current in the diode with $J_s = (q \cdot \frac{D_n}{L_n} \cdot n_{p0} + q \cdot \frac{D_p}{L_p} \cdot p_{n0})$.

In reverse bias, the current can be calculate exactly in the same way and gives the same expression with V< 0.

For the calculation of the current between plasma contactor and ambient plasma, we can make the same calculations. In this case we suppose that the dense plasma is not in expansion. It is like a fixed dense plasma bubble into another plasma (few dense), see figure 10.

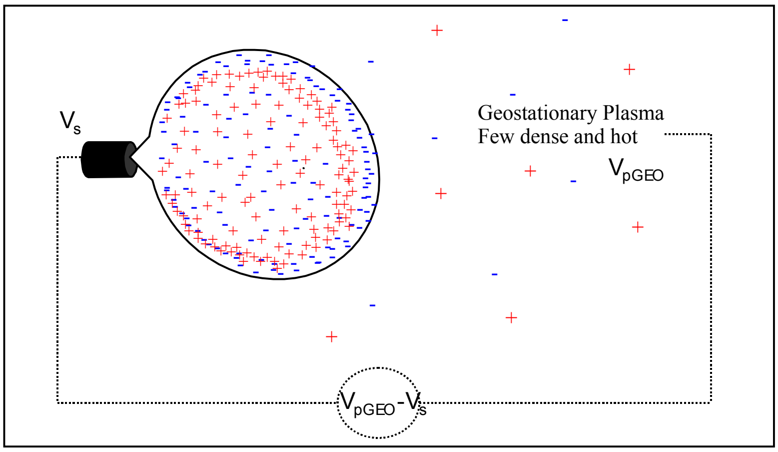

Figure 10.

As for holes and electrons of the junction, we can use the drift-diffusion equation for electrons and ions of the plasma. For so we can write $J_i = q \cdot n_i \cdot \mu_i \cdot E - q \cdot D_i \cdot \frac{\partial n_i}{\partial x}$ and $J_e = q \cdot n_e \cdot \mu_e \cdot E + q \cdot D_e \cdot \frac{\partial n_e}{\partial x}$ and we can calculate the barrier potential : $V_0 = \frac{kT}{q} \cdot \ln \frac{n_e^s}{n_i^{GEO}}$ with n_e^s the electrons density in the dense plasma bubble (so in the plasma plume of the plasma contactor or thruster) and n_i^{GEO} the ions density of the plasma in geostationary environment.

In the plume n_e^s is about 10^{15} m^{-3} and for geostationary environment n_i^{GEO} is about $10^6 m^{-3}$. So we find that V_o is about 20V – 40V (T_e = 1-2eV).

From this drift diffusion equation and from these assumptions, the electrons current calculation can be made exactly in the same way as for the PN junction with adapted boundary conditions. Finally we can write that the current circulating between the plasma source and the GEO plasma through the dense plasma bubble can be written as: $J = J_0 \exp[(qV/KT)-1]$ with $V=V_{pGEO} - V_s$. When the spacecraft is negatively charged, its potential is more negative than the potential of the GEO plasma and then V is positive.

In fact, this model is very simplified, nevertheless it is coherent with the plasma contactor current-voltage characteristic that has been measured (see figure 9) and it shows that the current can be calculated and taken into account when the drift-diffusion equation (fluid model) is used for electrons. For a more realistic model, it should be necessary to add a temperature equation. The plasma plume of the plasma contactor or thruster is cold (1-2 eV) whereas the plasma of the GEO environment is hot (few 10 KeV). Moreover, the temperature in the plasma plume varies.

We have assumed too that there is no expansion of the plasma plume and that it is like a fixed plasma bubble. This assumption is not valid as the principle itself of the plasma contactor and thruster is to continuously eject a dense plasma. So, in fact the plasma plume expands in the ambient GEO plasma. This means that the model for ions is more complex (Vlasov) with charge exchange collisions. This means too that electrons and ions don't have the same characteristic speed. For the same reason the assumption of stationary state is perhaps not really verified. Last, another delicate point is to determine the limit of the dense plasma. Nevertheless, we can think that a fluid model for electrons of plasma plume is more adapted to taken into account of the current circulation than the Maxwell-Boltzmann distribution.

This model has not been yet implemented in SPARCS but it is planned for next year.

Impact of the Plasma Contactor Effect on Differential and Absolute Charge on Spacecraft

We have seen before that the plasma contactor effect is to generate a conductive path like a circuit between the spacecraft and the ambient GEO plasma. We have seen too that when the spacecraft is charged relative to the ambient GEO plasma (the 0V), a current circulates between the spacecraft and the ambient plasma.

When the plasma contactor or the plasma thruster is directly connected to spacecraft ground, there is a current flow between conductive spacecraft surfaces and the ambient GEO plasma (0V) until the potential of the conductive surfaces of the spacecraft (the absolute potential) is equal to the potential of the ambient GEO plasma (0V). So, there is a direct neutralisation of floating potential of the spacecraft. This neutralisation is rapid, see figure 11.

Moreover, the particles of the secondary plasma (backflow) created by charge exchange collisions between primary ions and slow neutral atoms are attracted by the electric field generated by the differential potential (difference between potential of dielectric surfaces ϕ_s, and potential of the spacecraft ground ϕ_{PC}). For example if $\phi_s < \phi_{pc}$ as $\phi_{pc} = \phi_{pp}$ (plasma thruster connected to spacecraft ground and there is neutralisation of absolute potential), the ions of secondary plasma are attracted by ϕ_s and come to neutralise the surface until $\phi_s = \phi_{pc}$, see figure 11.

When the thruster is perfectly isolated from spacecraft ground, the plasma thruster provides particles (secondary plasma) which are attracted by potential of spacecraft surfaces (dielectric and conductive). In the same time, due to the plasma contactor effect, there is a current flow between thruster and the ambient plasma environment until ϕ_{pp} =0V, see figure 12. So, finally there is indirect neutralisation of floating potential (slow) and differential potentials.

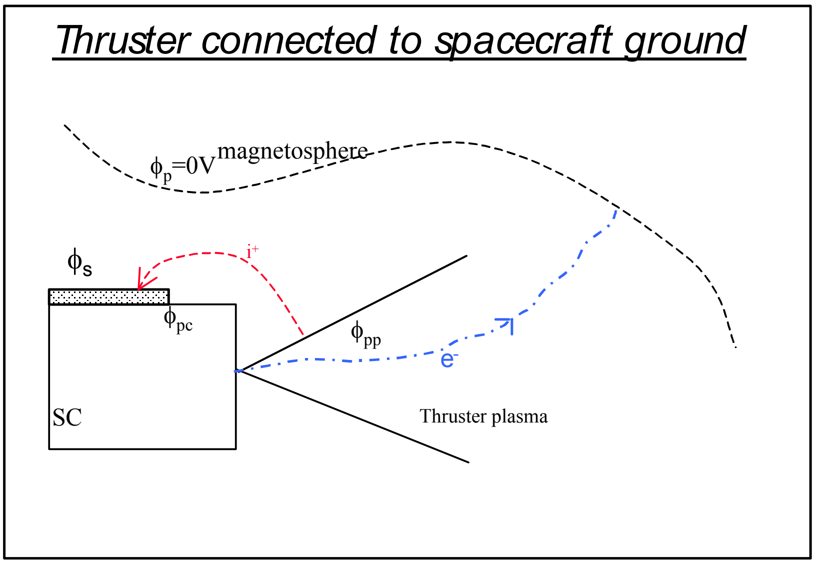

Figure 11. Thruster connected to spacecraft ground

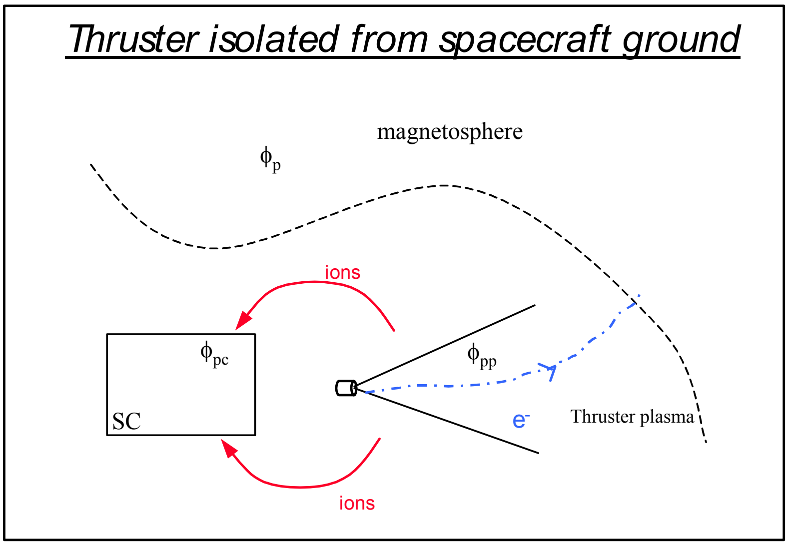

Figure 12. Thruster isolated from spacecraft ground

In a realistic case, as it is the case on Alcatel platforms, the thruster is not perfectly isolated from spacecraft ground. There is a parasitic electric circuit between thruster and spacecraft ground. As for a perfectly isolated thruster, the particles of secondary plasma are attracted by potential of spacecraft surfaces and neutralise them, see figure 13. And in the same time there is a current flow between spacecraft conductive surfaces (spacecraft ground) and the ambient plasma through the parasitic electric circuit and the conductive path provided by the plasma plume of the thruster (plasma contactor effect). So there is neutralisation of potentials but the dynamic and the neutralisation phenomenon depends on the characteristics of the parasitic electric circuit.

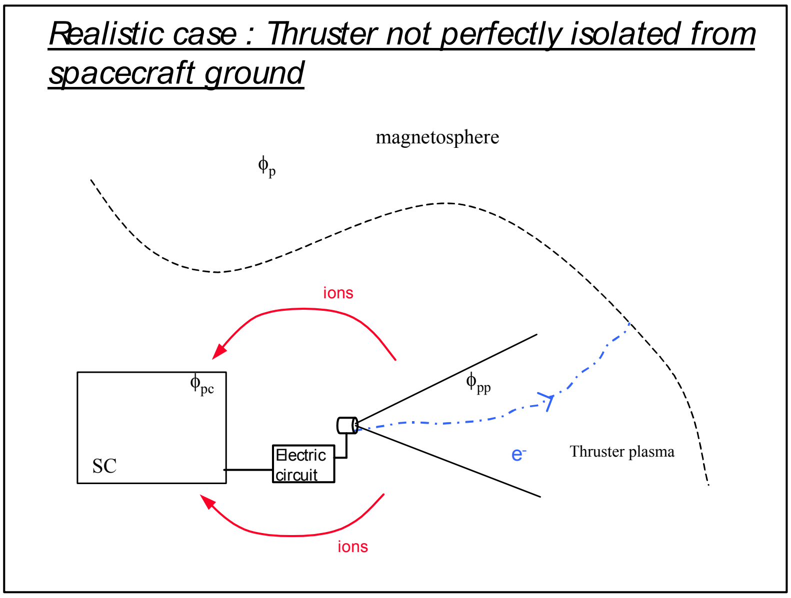

Figure 13. Thruster not perfectly isolated from spacecraft ground

<u>Conclusion</u>

The modelling of the plasma contactor effect of a plasma thruster model is essential to simulate the impact of the plasma thruster on spacecraft charging. During the development of SPARCS we have seen that the generally accepted hypothesis of Maxwell-Boltazmann distribution for the electron of the plasma plume is not adapted to take account of the plasma contactor effect. As the plasma contactor physical mechanisms are similar to the ones of the PN junctions, we think that a fluid model for electron is more adapted to take into account the current circulation between spacecraft and GEO plasma through the thruster plasma plume. Nevertheless, there are still some difficulties like the determination of the neutrality region limit, the necessity to add a temperature equation and the validity of stationary state. For the Alcatel platforms, the parasitic circuit between thruster and spacecraft ground should be modelled too. The fluid model for electron will be implemented in SPARCS next year. Alcatel will have then a complete, innovative and accurate tool for spacecraft charging analysis.

References

1. A critical Overview on Spacecraft Control Methods. Shu T. Lai, Air Force Research Laboratory, 6th Spacecraft Charging Technology Conference.

2. Active Devices for the control of S/C charging. Alberto MATUCCI, Proel Technology Division of Laben, Cours de technologie spatiale. Environment Spatial prévention des risques liés aux phénomènes de charge. juin 96.

3. SPARCS: An Advanced Software for Spacecraft Charging Analyses. S. Clerc, S. Brosse, Alcatel Space, M. Chayne-Yook, Inria, 8th Spacecraft Charging Technology Conference (Huntsville, Alabama)

4. An Experimental investigation of the plasma contacting process. Paul J. Wilbur, John D. Williams, Colorado State University, AIAA-87-0571

5. Hollow-cathode Plasma contacting insights gained from the electrodynamic tether mission. P.J. Wilbur, D. Burtner, Colorado State University, IEPC-99-218.

6. Plasma Sources for Spacecraft Neutralization. V. Davis, I. Katz and M. Mandell, M. Mandell. AIAA 90-1556.