Numerical Simulations Developed at Alcatel Alenia Space for Electric Propulsion Effects on Satellite

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Abstract: **This paper presents the recent investigations and developments achieved by the Research Department of Alcatel Space (ASP) in the field of electric propulsion interactions with satellite on both disturbance and degradation effects and electrostatic impact of plasma thruster on spacecraft charging. ASP has now a good experience in the interactions between the plasma plume and the spacecraft surfaces and always deepens its knowledge of these numerous phenomena and on the numerical methods to be settled. For several years, ASP has been developing a software named ISP (Interactions Spacecraft Propulsion) with Russian team of Moscow Aviation Institute (MAI) to predict the electric plume effects (mechanical and thermal disturbances, erosion and deposition of sputtered particles). The software is continuously improved to make it more efficient and accurate. Recently, the plasma jet model has been modified and improved to get more accurate sputtering results in the periphery zones of the jet (back-flow). Moreover an orbitography module has been added to enlarge the capabilities of ISP to the disturbance solar torque prediction and to the shading zones on solar array determination for power budget calculation. In parallel, the Research Department has developed a software SPARCS (SPAcecraft Charging Software) which simulates the electrostatic charge of a spacecraft in geostationnary plasma. The next version of the code will be able to modelling the impact of the plasma thruster on the spacecraft charging. In a first part, we will present the problem of the Maxwell-Boltzmann distribution to correctly model the spacecraft charging modification due to plasma thruster. The problem is to correctly estimate the equilibrium potential of the plasma at the thruster exit. 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. 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**

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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 can characterise the equilibrium after neutralisation. The isothermal approximation in Maxwell-Boltzmann equation give a rather large value for the equilibrium potential barrier. We show that an isentropic model leads to a more realistic equilibrium.

I. Introduction

THE always increasing of satellite on orbit life and mass make the Electric Propulsion more and more attractive for station keeping on geostationary telecommunication satellites. Alcatel Alenia Space will implement the plasma SPT 100 on its ongoing satellites for north-south station keeping. However, the introduction of electric propulsion subsystem on our telecommunication satellite require to study its potential repercussion on the other systems of the satellite. For several years the AAS Research Department has worked on the interactions between the plasma plume and the spacecraft surfaces and has developed, in collaboration with external society , two software ISP and SPARCS. The software SPARCS (SPAcecraft Charging Software) is developed by the AAS Research Department. It simulates the electrostatic charge of a spacecraft with plasma thruster in geostationary environment. ISP (interactions Spacecraft Propulsion) has been developed with the collaboration of MAI (Moscow Aviation Institue) since 1994 to predict the mechanical and thermal disturbances, erosion and deposition of sputtered particles. This software is continuously improved and some new modules has been recently added.

II. SPARCS

SPARCS is a 3D code which is 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. The current version of the code is specifically designed for low-density collisionless and hot plasma found in geostationary environment during substorm[1]. This code is operational and is currently used at Alcatel Alenia Space to perform charging computations in geostationary environment. The next version of this code will include the modelling of the thruster plasma plume and its impact on spacecraft charging.

A. Problem of Maxwell Boltzmann distribution generally used to modeling the electrons in the plasma plume

The propulsion plasma is characterised by fast and slow ions and by cold and dense electrons. 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 $r \to \infty$, 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. The problem is to correctly estimate the equilibrium potential of the plasma at the thrusters exit. In fact, there is a 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 and to estimate the equilibrium potential at the thrusters exit. Without this effect we could not explain the neutralisation of potentials observed in orbit.

B. 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, (Fig.1).

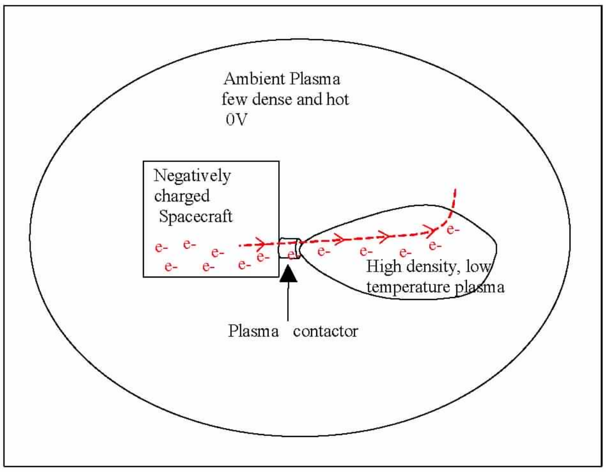

Figure 1. Plasma contactor principle.

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, (Fig. 2).

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 Fig. 2) and a electric field appears which retards electrons until there is no net electron flow [3]. A space charge region (a potential barrier) is created.

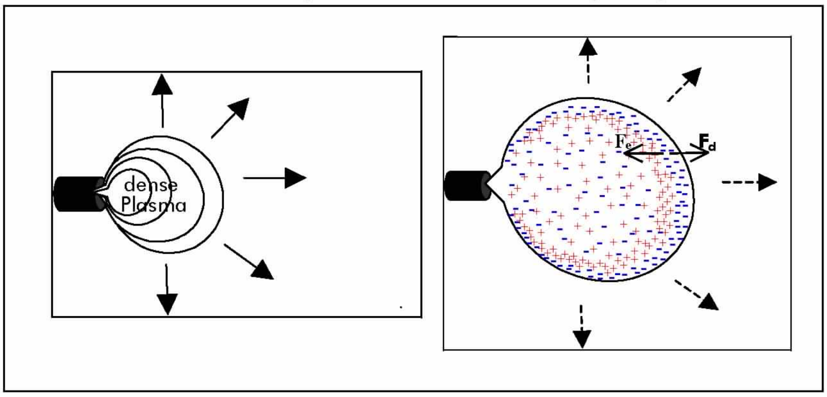

Figure 2. Space charge region

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 Fig. 3.

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

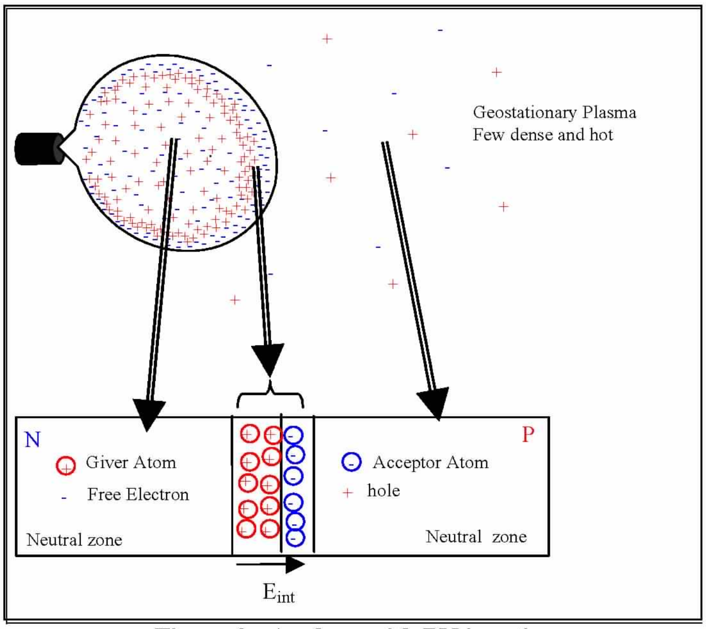

Figure 3 : Analogy with PN junction

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 Fig. 4.

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.

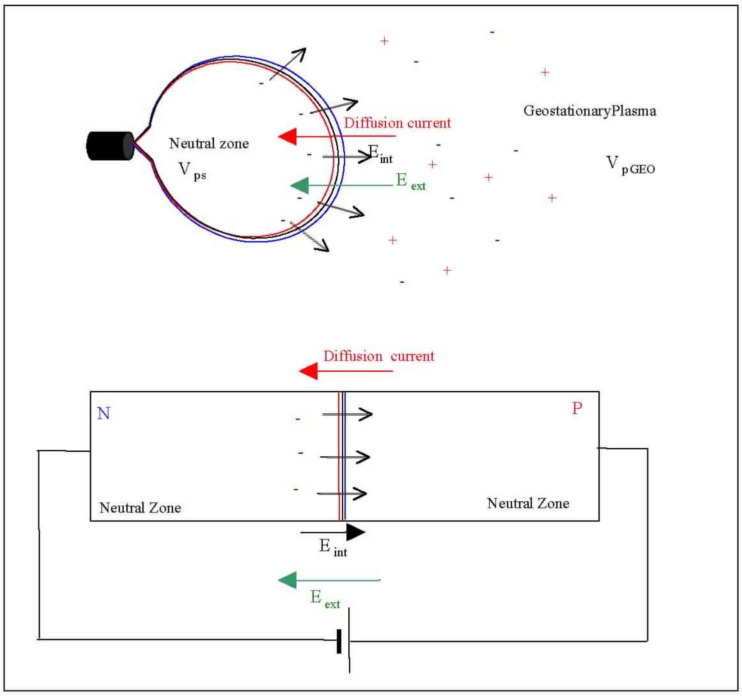

Figure 4 : Forward bias

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 Fig. 5.

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.

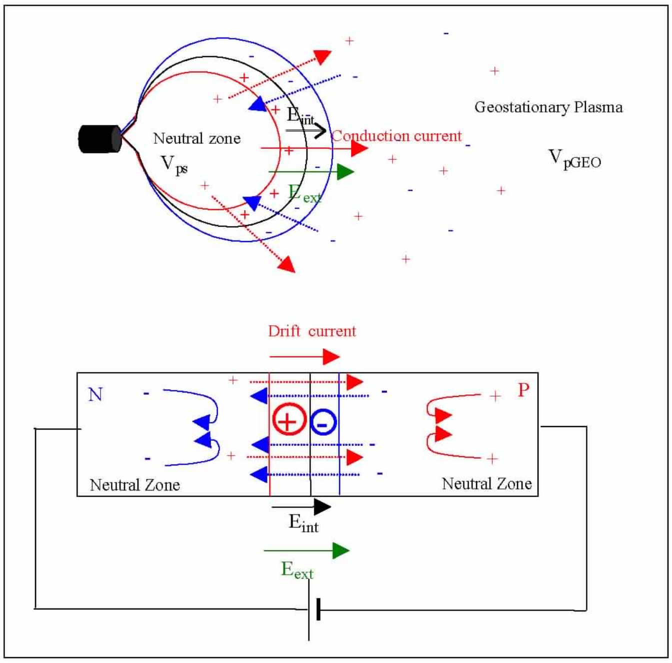

Figure 5 : Reverse biais

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 in Fig. 6 that they are very similar [2].

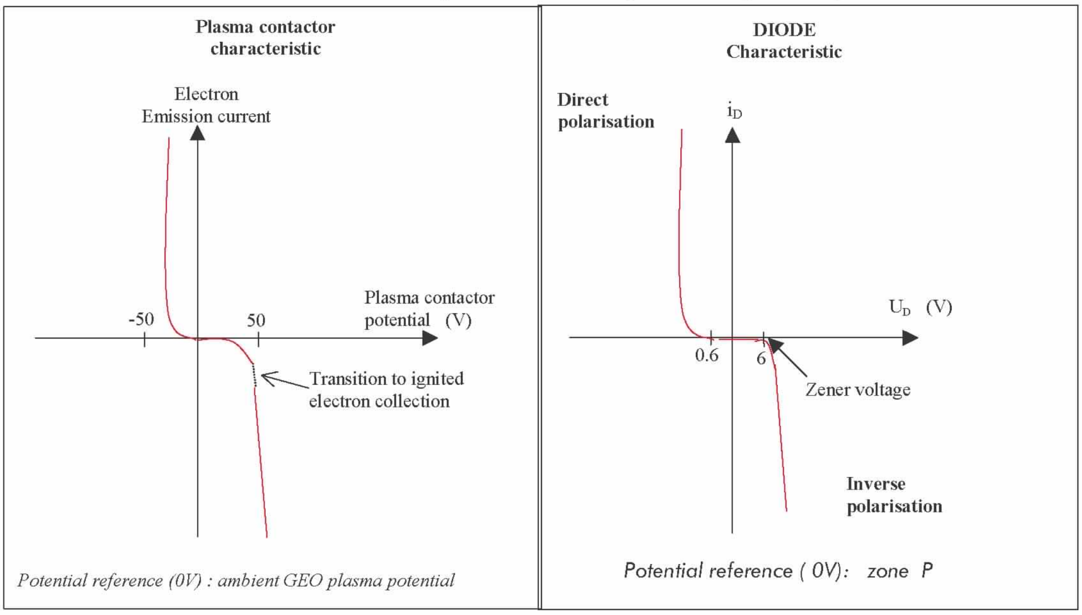

Figure 6 : Diode and plasma contactor current/voltage characteristic

C. Impact of the plasma contactor effect on differential and absolute charge of 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, (Fig. 7).

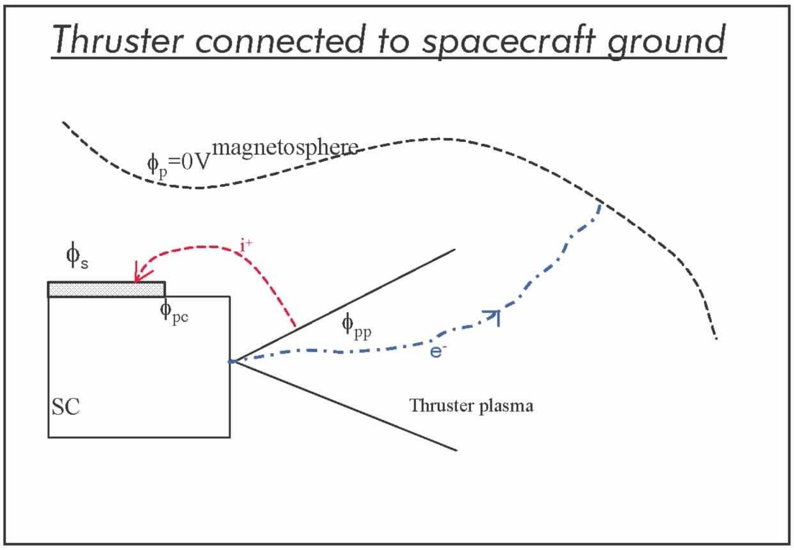

Figure 7 : Thruster connected to spacecraft ground

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 $\phi_s = \phi_{pc}$, (Fig. 7).

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, (Fig. 8). So, finally there is indirect neutralisation of floating potential (slow) and differential potentials.

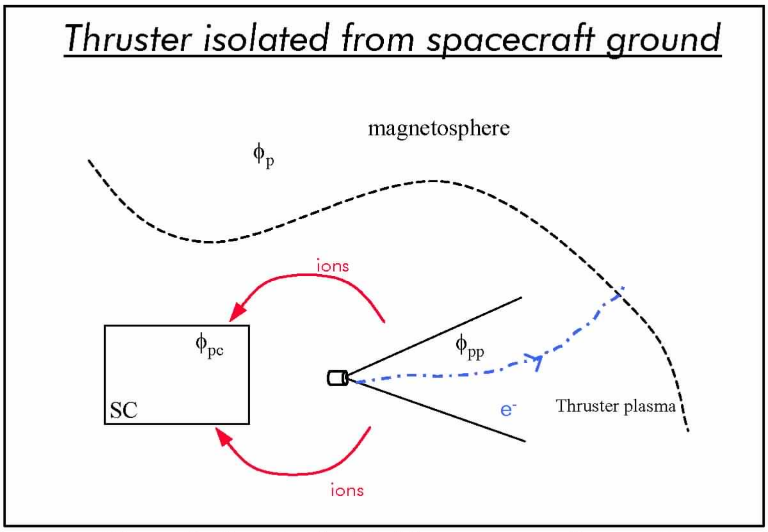

Figure 8 : thruster isolated from spacecraft ground

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 Fig. 9. 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.

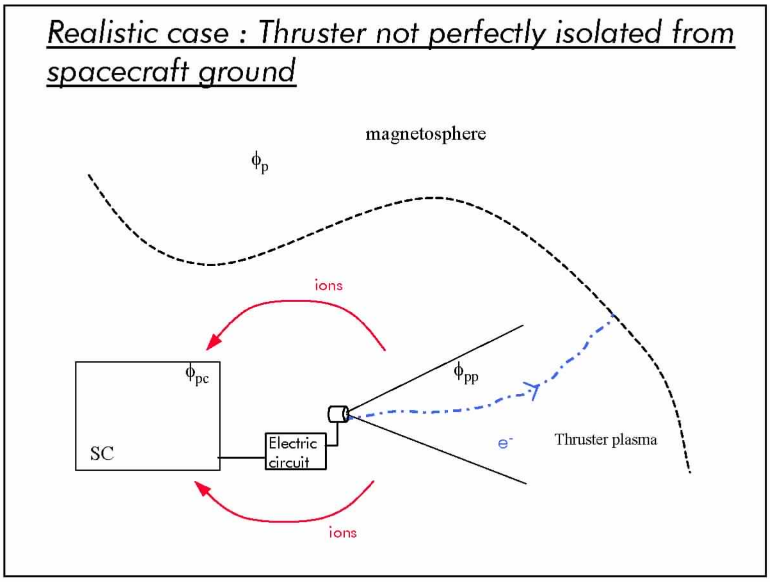

Figure 9 : Thruster not perfectly isolated from spacecraft ground

D. Plasma thruster modeling

We have seen that a Maxwell-Boltzmann model for the plume electrons is unable to predict the expansion of the plume far from the thruster and gives an incorrect value of the equilibrium potential. On the other hand, it is desirable to keep a fluid model which gives a simple description of the electron population. In fact it can be seen that the problem of the Maxwell-Boltzmann model is the implicit assumption of a constant temperature throughout the plume. Obviously, the temperature of the electronic fluid has to dropped as it expands in space if no external energy is provided.

Boyd and Yim[4] proposed a detailed fluid model using an energy conservation equation. However it is also possible to obtain a satisfactory solution with a simple isentropic model in which the electronic pressure varies like $N_e^{2/3}$. This model accounts for the temperature drop during the adiabatic expansion. The electrostatic potential decreases rapidly at the thruster exit then reaches an asymptotic value as the plasma density vanishes.

As seen in the previous section, at equilibrium a potential barrier is established between the plume and the environment ; this potential barrier prevents the electrons from drifting outside and is such that electrostatic forces compensate pressure forces. This value determines the potential difference between the anode exit potential and the reference plasma potential at infinity. The equilibrium value predicted by the isothermal Maxwell-Boltzmann model is very large and depends strongly on the density of the background plasma. The isentropic model by contrast predicts a potential barrier of –2.5 times the cathode electronic temperature, independently of the background plasma density.

Fast ions are modelled through a kinetic description. Because of their large kinetic energy, the influence of the electrostatic field can be neglected as a first approximation. The density of neutrals is determined from the calculation of the solid angle subtended by the anode exit ring[5]. The combination of these two density fields enable the determination of the source of slow Xe^+ ions through charge exchange inelastic collisions. We chose to describe the distribution of slow ions with a fluid model. Here a detailed model including momentum and energy conservation cannot be avoided. The electrostatic potential can be recovered either by the Poisson equation or a quasi-neutrality assumption.

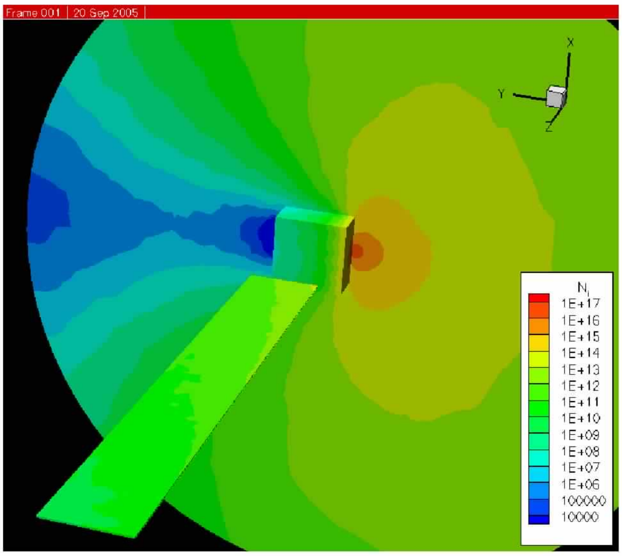

Figure 10 : Charge Exchange (slow) ions density around spacecraft (thruster located on the +Y wall).

III. ISP

ISP software was originally developed to give to the AAS engineers a real and efficient capability to optimize the integration of a plasma propulsion system on board the satellites. Hence the first developments dealt with the prediction of the interactions between the electric propulsion and the sensitive surfaces of the satellite which are to be taken into account in the satellite design and attitude control: disturbance forces and torques, thermal impact and surface degradations (erosion and sputtered particles re-deposition). As it was already presented with details [6, 7, 8], a “simple” multi-fractional model of the plasma plume is used and briefly recalled here. The model describes the ion space and energy distribution. The ion flow is divided into separate fractions representing each a mono-velocity class of ions with an average energy. A model of source point with varying intensity on angle is implemented to propagate the distribution of the particles concentration in the whole space for each fraction. With the following assumptions: no collisions along the particles trajectories, no exchange between fraction and constant velocities along the trajectories, the propagation of each ions fraction can be separately calculated. Using this plume model for

the calculation of the energy, concentration and current density of the ions in the whole space allows the calculation of the interaction of energetic ions with satellite surfaces. The erosion model takes into account the local current density and concentration of ions and the sputtering coefficient of the impinged materials. Numerous experimental campaigns have been realized to fulfill the ISP material data base with the sputtering coefficients depending on the incident ion energy and angle.
In an aim of efficiency and enhancement of the software capabilities, several capabilities and modules were added in 2001 concerning mainly:

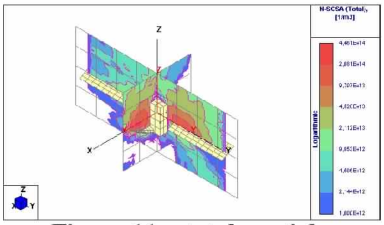

Figure 11 : total particle concentration

- the calculation of the parameters of the SpaceCraft Self Atmosphere (SCSA): SCSA is mostly caused by the outgassing of the satellite surfaces, particles (charged or not) coming from chemical or electric propulsion and sputtered particles from the surfaces impinged by the plasma plume. This functionality allows to calculating both the concentration of the particles all around the satellite and the contamination of the surfaces taking into account complex phenomena,
- the erosion of the discharge chamber of a SPT100 and the angular distribution in the plume of the sputtered particles: the aim of this module is to predict the contamination of the satellite surfaces with the metal and isolator sputtered components coming from the electric thruster,
- the prediction of the modifications of the surfaces properties when contaminated: this module is necessary to estimate the risk of degradation of sensitive devices performances.

Recently, the capabilities of ISP were even more enlarged and a new collaboration between the Moscow Aviation Institute and Alcatel Alenia Space was conducted. The goal is on one hand to improve the model of the plasma plume and on the other hand to implement an orbit generator for solar pressure or shadowed zones calculations.

- The prediction of the erosion rate on solar array is of major interest regarding the electric propulsion interactions with satellite surfaces. Due to the relative location of the thrusters with respect to the solar arrays, the calculation of erosion generally takes place in the large divergence angle zones of the plume (>60°). The existing plasma plume model for SPT100 in ISP showed some differences in these zones with experimental data from Absalamov[9]. This can conduct to an under-estimation of the erosion rate. Hence, a new module called ISP Jet Maker 1.0 has been settled and is now available in the ISP3.0 package. Its aim is hence to have the possibility both to modify the parameters of the multi-fraction model in ISP in order to improve the peripheral zones and also to create a new multi-fraction jet model based on data coming from experimental tests or numerical calculations for any other electric thruster.

The results of probe measurements are usually used as initial data for the jet model creation. In vacuum test facilities, the probes, Retarding Potential Analyzers (RPA), are placed at several divergence angles and at a distance R_0 in the jet. However as experience shows, such data direct use is delicate. Indeed the initial RPA data can be very noisy and a great error can occur in the calculated ion function of distribution over energies. Besides, the RPA data in the peripheral zones are not very reliable because of the local small current density. A processing of the measurements is therefore realized to make possible the creation of an accurate plume model.

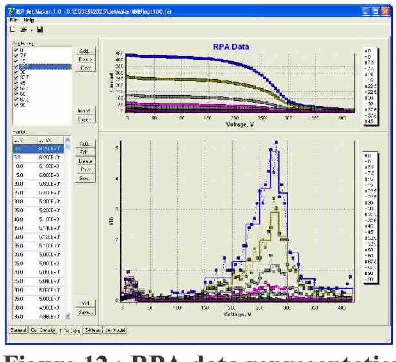

Figure 12 : RPA data representation

Several functions are available for the current density dependence on divergence angle. These functions allow to obtaining the distribution of the current density with respect to the ion energy for each divergence angle (Fig. 12). In order to control the ion average energy in the jet, functions of average energy dependence on the divergence angle are also available and chosen.

The creation of the multi-fraction model is based on an iterative process which is briefly described below. The ions whole range of energy is iteratively divided into fractions starting from the lowest energy fraction up to the greatest. At each step the current density of the considered fraction f_n is computed from the previous one f_{n-1} as $j_{f_n} = j^{old}{}_{f_{n-1}} \cdot \rho(\theta)$ *and* $j^{new}_{f_{n-1}} = j^{old}_{f_{n-1}} - j_{f_n}$. $\rho(\theta)$ is a weight function of the energy fraction f_n deduced from the RPA data and adequately smoothed. At the first step, $j_{f1}(\theta) = j_0(\theta)$ which is the total current density of the jet. This step-by-step method permits to always fit the thruster parameters: thrust and flow rate.

This method permits to build a multi-fraction model of plasma jet from experimental data to realize the calculations of interactions with satellite surfaces in ISP. It also permits to eventually modify the existing jet parameters (fraction or distribution functions) taking into account the constraints of the thruster parameters.

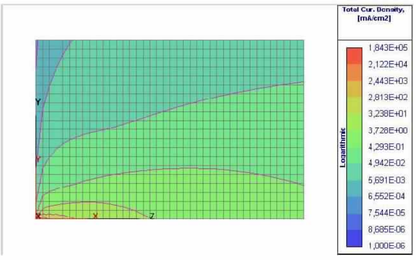

Figure 13: Plume representation example

For example, for the peripheral zones without RPA data, an ion unimodal function of distribution over energies is settled and an interpolation is realized with the function of distribution in the core zone of the jet (with RPA data). The analysis of the existing data shows that there are no great changes in the distribution function at the plume periphery. Indeed in this zone the average ion energy is very close to the value of the jet potential[10,11]. So, a rather good approximation of the jet structure can be obtained with an even very rough representation of the function. Usually the ion average energy in this zone is about 10-20 eV. The calculation erosion rate in the peripheral zone is a very difficult problem, because the ion energy is close to the sputtering threshold energy. Further experimental and modeling investigations have to be done to get more accurate information of both ions energy and sputtering threshold. The figure 13 shows a graphical representation of the plasma jet of a SPT100 in ISP with peripheral zones.

- Since its first version ISP is able to calculate the lighting on a surface coming from a light point source and taking into account the possible shaded zones. This calculation is realized with a ray-tracing module. The opportunity was taken to enlarge this capability and the new ISP version (ISP3.0) is now able to calculate the solar illumination with shadowing and disturbance solar pressure on any orbital configuration. An orbit generator is now available in the software. The Kepler's parameters of the orbits of both earth and satellite have to be given. Numerous standard attitudes for the satellite orientation are available according to the mission of the satellite. Moreover the pointing of the rotating appendices (solar array, antenna…) has to be specified through the pointing vector and rotation axis and the kinematics of the element is automatically computed (Fig.14). The solar illumination of the surfaces is calculated taking into account the satellite orbital location and pointing and the possible shadowing by satellite elements or earth (eclipse). The direct solar flux, the earth reflection of the solar flux (albedo) and the earth radiation flux (Infra Red) are considered. The calculation of the solar illumination on the solar cells has been improved.

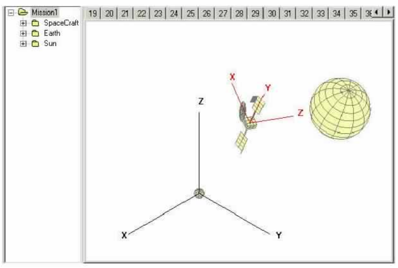

Figure 14: Orbit representation

Each solar cell can be automatically subdivided into mesh cells (up to 100 mesh per cell) for which the shaded zones are calculated. This process allows to increasing greatly the accuracy of the calculation of the solar illumination in order to make possible a refined thermo-electric analysis of solar array (Fig.15).

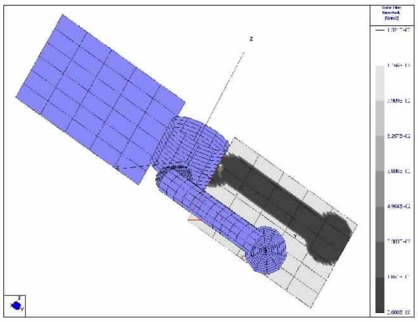

Figure 15: Solar flux and shaded zones

The solar pressure calculation is necessary to the prediction of the disturbance solar torque which are taken into account in the attitude and orbit control system. The calculation is realized taken into account the coefficients of absorption, emissivity and specular and diffuse reflection of the considered material. These data are stored in the material data base of the software.

This new capabilities represents a real advantage for the engineers who are now able to realize both the prediction of plasma plume effects and the calculation of the disturbance solar torque and shadowed zones along the different orbit locations with a unique tool and especially with a unique geometrical model.

IV. Conclusion

Fruits of a continuous effort, Alcatel Alenia Space has drastically increased its knowledge concerning the electric propulsion interactions with satellite. Based on theoretical studies and international collaborations, the Research Department has set out tools ISP and SPARCS to predict and possibly to avoid the damages on satellites on boarding the electric propulsion. The first releases of these code are now operational and are used to made the analysis. Nevertheless these code are continuously improved to make them more efficient and accurate.

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