MODELING OF THE PLASMA ENVIRONMENT OF A FEEP MICRO THRUSTER WITH PICUP3D SIMULATION CODE: SAMPLE RESULTS

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Abstract

Electric thrusters are planned to be used on a broad scale on new generation spacecraft as main propulsion engines or for attitude and orbit control. In parallel many theoretical and experimental works about their performances and functioning are still in progress. One of the issue is their interaction with the surrounding plasma environment. This paper presents a study performed at the European Space Agency (ESA) for modelling the interaction between a Field Emitter Electric Propulsion (FEEP) system and a surrounding ionospheric plasma. A detailed 3D PIC model of the FEEP system and of its environment has been performed, using the PicUp3D code, developed in the framework of the SPINE network (http://www.spis.org). The model takes into account a detailed geometrical model of the inner volume of the thruster, including all electrodes and the aperture geometry, and the surrounding ambient plasma in a large computational space. This study helps to validate acceptable design in order to reduce back-streaming electron currents from ionospheric type environment and to assess the FEEP engine plume neutralisation process.

Introduction and Objectives of the Study

There is a growing interest for the use of electric propulsion systems in space as main propulsion engine or for attitude and orbit control. Field Emitting Electric Propulsion (FEEP) micro-thruster engines are being considered for drag compensation for low altitude Earth observation satellites. Such devices are characterised by a low current of high energy ions emitted by a thin anode and may interact in several ways with the surrounding plasma environment [cf e.g., Tajmar and Wang, 2000]. Two types of interactions are considered in this paper: (1) the neutralisation process of the plume by the surrounding plasma and (2) the current collection of ambient plasma by the emitting electrode.

The FEEP engine considered in this study is constituted by a very narrow hollow needle mounted on a tank of liquid Indium and biased at a very high potential (a few kV) with respect to an extractor electrode which is a circular ring located at a very short distance from the needle's tip. Although such a design has a long in space experience as a charge alleviating device on magnetospheric spacecraft [cf e.g. Torkar et al., 2001] some uncertainties remain on its behaviour in an ionospheric type of environment, i.e. when the surrounding plasma density is high. In particular, the number of electrons which may propagate from the outside to the anode is an issue for the control of the engine thrust and for the survivability of the needle which may be destroyed by the heat. Therefore, several tests and numerical modelling have been performed in order to model the interaction of the FEEP system with a surrounding ionospheric plasma. Some sample results of the numerical simulations are presented in the following while more detailed and quantitative results will be published in a forthcoming paper.

Modeling Approach

Three types of inputs are required for this study: (1) the environment data, (2) the geometry, (3) the numerical model of the interactions. They are discussed in the following.

On very low altitude orbits (a few hundred kilometers), the ambient plasma environment is of ionospheric type. The density may be of the order of 10^{11} m^{-3} in the day side F layer region to 10^{9} m^{-3} in the night side one. The temperature is of the order of 0.1 eV. If the spacecraft is equipped with a main ion engine system of the SPT type the ambient environment may be dominated by the charge exchange plasma with a density of typically 10^{11} m^{-3} to 10^{12} m^{-3} and a temperature of a few eV [cf e.g., Tajmar, 2001; Tajmar and Wang 2001]. For the purpose of this study, one used a rather high density plasma environment with a density of 10^{12} m^{-3} and a temperature of 0.1 eV. This corresponds to a Debye length of the order of 10^{-3} m.

The basic geometry of the FEEP engine is shown on Figure 1. Indium ions are emitted from a needle at a potential which may vary from 6 to 10 kV with respect to the ring shaped accelerating cathode. The narrowest diameter of the aperture diameter is 15 mm. The needle diameter is 0.25 mm. A repelling ring with negative biased potential is foreseen to prevent electrons from outside the thruster to propagate to the needle.

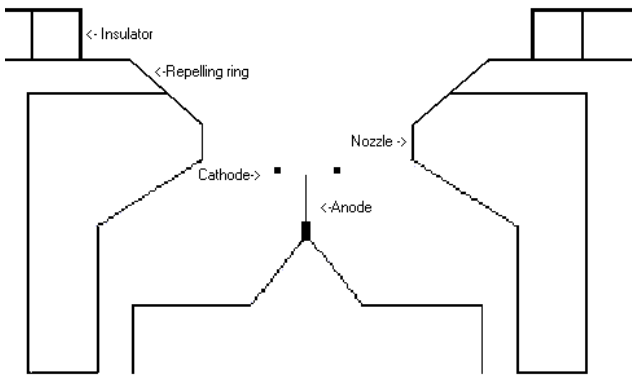

Figure 1. Sketch of the FEEP engine geometry (not on scale).

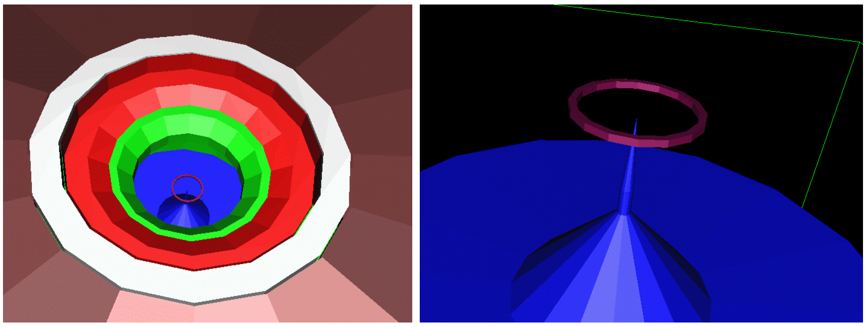

Figure 2. 3D views of the geometrical model of the FEEP thruster. One can see the anode (blue) constituted by the needle and the tank and the accelerating ring (pink). In addition a repelling ring can be used outside the aperture.

3D models of the complete system were generated with a CAD tool and described in VRML format. It allowed a description of the surface details as low as 0.25 mm. However, a coarser resolution had to be used for the potential solver (cf below). The FEEP micro-thruster environment is investigated as a stand alone body. The influence of any other part of the spacecraft is neglected. The ground potential of the thruster is kept fixed at 0V.

In this study only stationary regimes are investigated. The dynamics of the energetic ions emitted by the needle and accelerated by the anode is neglected. They are treated as an uniform static space charge in a cone of 15 degrees aperture angle. The ambient plasma environment in stationary regime is described by the set of the Poisson and Vlasov equations which are solved with the open source 3D PIC simulation code, PicUp3D, described in this spacecraft charging technology conference and the previous one [Forest et al., 2001]. The boundary equations are given by the potential on the material surfaces including the electrodes. The simulation box size is chosen such that it contains entirely the electrostatic sheath and therefore, the potential at the box boundary is set at 0V. Typically a 0.3 meter box size have been used for the simulations.

PicUp3D is solving the Poisson equation on a rectangular mesh. This imposed a severe constraint on the ratio of the spatial resolution to box size for a given memory size. The highest spatial resolution used in this study was a mesh size of 0.75 mm. While the largest computational grid used was constituted of 256x256x256 nodes. The needle itself was too thin to be accurately represented in the model and was treated as a one dimensional boundary condition for the potential solver.

Simulation were performed using a number of computer particles between 2.10^{6} and 3.10^{6} in order to have a good statistical basis for the estimate of particle density and collected currents. An ion to electron mass ratio equal to 100 was used to reduce the computation time. Nevertheless, the simulations took a long time before reaching a stationary regime. Typically, the runs had to last for more than 300 x $1/\omega_{pe}$ simulation time (where ω_{pe} is the plasma frequency). This corresponds to several days with a time resolution of dt=0.05 $1/\omega_{pe}$ on a PC with a processor at 1GHz.

Sample Results

A first series of computations was performed without repelling negative ring around the aperture and with a relatively thin spacecraft wall. It was found in this case that the potential at the aperture was significantly positive (a few hundred volts) and the sheath extended by several centimeters away from the aperture. It would have resulted a backstreaming electron current to the anode above the acceptable level. On one hand it allowed to conclude that neutralisation of the FEEP plume space charge by the ambient ionospheric plasma was very efficient (neutralising device may still be needed to keep the spacecraft potential at moderate level). On the other hand, however, it indicated that a negative repelling ring is absolutely mandatory for preventing backstreaming electrons to the emitter. Another series of simulations was used to evaluate the required geometry and potential of this repelling ring. Sample results of this second series are presented in the following.

In Figure 3 the equipotential contours in the x-z plan are shown when computed in vacuum with an anode at +9 kV, a cathode at 0 V and a repelling ring at –2 kV. It can be seen that there is a negative barrier of about -450 V at the aperture of the thruster.

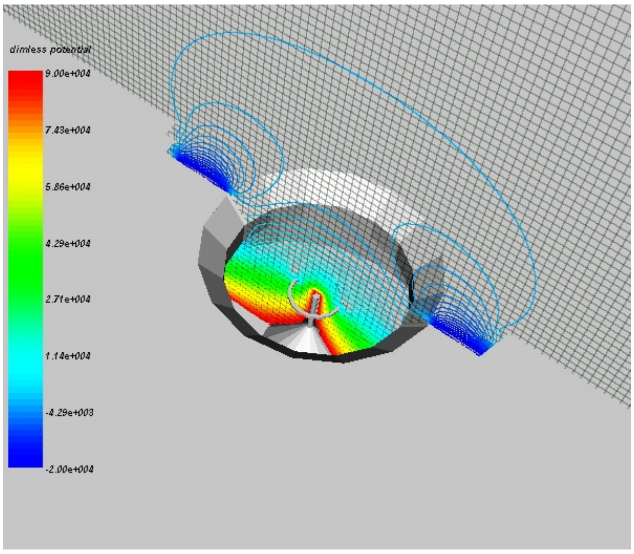

Figure 3: Equipotential in the x-z plan computed in vacuum of Vemitter= +9kV and Vrepel=-2kV. Potentials are expressed in k_BTe/e.

The effect of the ambient plasma and especially of the ion beam (with ion current, I_{beam}= 550 μA) space charge is shown on the equipotential contours of Figure 4. The barrier of potential is now of about –300 V. It is slightly decreased compared to the vacuum case but it is still strong enough to maintain the backstreaming current below an acceptable level. With the same configuration it was found that a repelling ring of –1 kV instead of –2 kV still lead to a potential barrier of –140 V. It must be noted that an unwanted consequence of the negatively biased rings is the creation of secondary electrons due to ion impacts which could in turn propagate to the anode. This phenomena had to be modelled as well but related results are not discussed here.

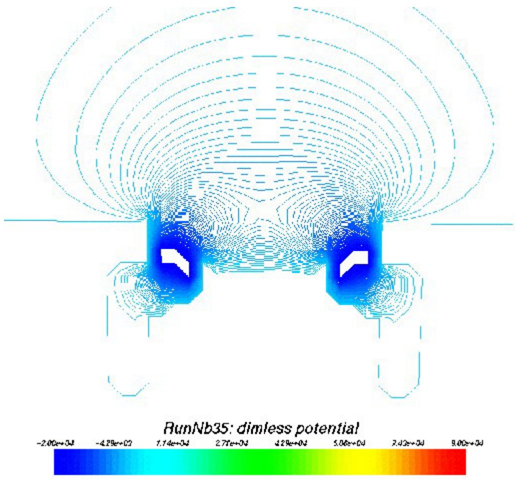

Figure 4. Equipotential in the x-z plan computed in an ionospheric plasma of Vemitter= +9kV and Vrepel=-2kV. Potentials are expressed in k_BTe/e.

Another design was investigated with a repelling ring located deeper inside the aperture. An example of the results for this new location and a bias potential of –1 kV is shown in Figure 5. In this case, no electrostatic barrier can be established along the direction of the ion beam and the number of backstreaming electron would have been critical.

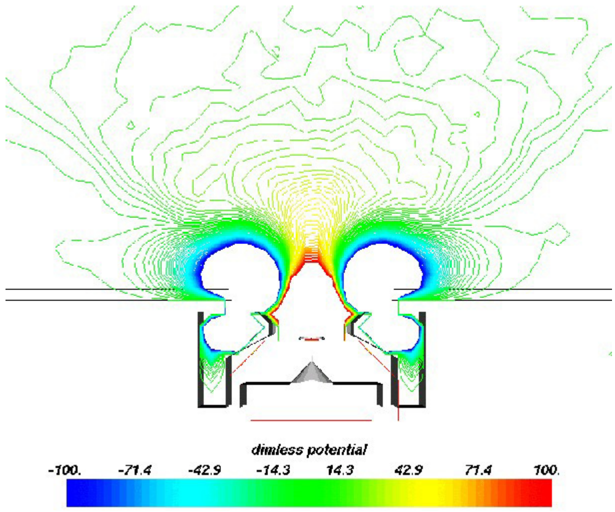

Figure 5. Same as Figure 4 but with the repelling ring at –1 kV and located closer to the anode. Potentials are expressed in k_BTe/e.

Finally, it must be noted that at low altitude, spacecraft are in a meso-thermal regime, meaning that the spacecraft velocity is lower than the electron thermal velocity and larger than the ion thermal velocity, therefore, in principle, the spacecraft velocity has to be taken into account in the ion dynamics. The effect on the ion plume when a FEEP thruster is emitting perpendicular to the ram direction is shown on Figure 6. Once can see that the equipotential contours are now asymmetric, however, it was found that the influence on the magnitude of the largely negative potential barriers was negligible.

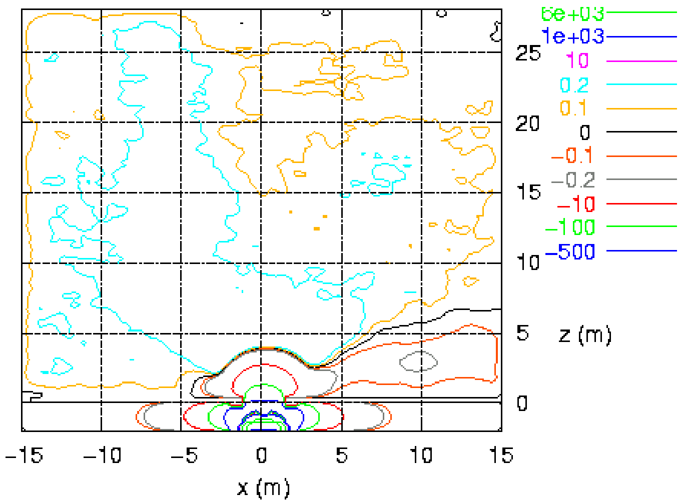

Figure 6: Ram effect on the electrostatic potential contours around a FEEP micro-thruster emitting perpendicular to the ram direction.

Conclusion

The PicUp3D code has been used to study various electrical configurations around a FEEP thruster aperture. It was observed that the effect of the beam space charge and the high potential electrodes of the FEEP engine is to expand the electrostatic sheath outside the aperture by about 0.2 m which is much more larger than the Debye length. The neutralisation of the plume space charge by ambient ionospheric plasma takes place within this distance. Potential barrier to prevent backstreaming electrons flux to the anode are mandatory but can be easily established with the help of a repelling ring-shaped electrode around the aperture. However, the magnitude of the barrier strongly depends on the detailed inner geometry and the setting of the various electrodes of control. Another effect which has to be taken into account is the current due to secondary electrons generated on the repelling electrode. This work confirms the capabilities of PicUp3D to model complex geometrical structures and plasma conditions, taking into account a very large range of ratio electrode potential to plasma thermal energy (10^4 in this study). A major limitation of this study results from neglecting the possibility of charge accumulation on insulators Another major limitation result from the poor spatial accuracy currently allowed by the use of the rectangular mesh for the Poisson solver. Improvements of the code foreseen in the coming few months would help to address this issue and allow accurate determination of the electrical current on each surfaces.

Acknowledgments

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