DOUBLE STAGE HALL EFFECT THRUSTER DEVELOPMENT ACTIVITIES AT SNECMA

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Abstract

To prepare the development of future versatile thrusters Snecma is currently working on a concept of Double Stage Hall Effect Thruster. This concept is based on the separation of the two main functions in Hall effect thrusters : ionisation is performed in the first stage while acceleration is achieved in a second stage.

First promising results obtained with different prototypes DSHET using magnetic ionisation stage are presented.

1. Introduction

With their first in-flight operations onboard western satellites (Intelsat 10-02, Inmarsat4-F1, MBSAT) following the large experience accumulated onboard Russian Spacecraft, electric propulsion systems based on Hall effect plasma thrusters are now widely recognised as a mature technology for both telecom satellites and scientific probes.

After 4600h of successful operation as primary propulsion allowing the ESA SMART-1 Spacecraft [1, 2] to reach its operational orbit around the moon on beginning of this year the Snecma's PPS® 1350-G is the first plasma thruster fully based on Europeans technical standards and processes to be operated in flight.

If current applications of Hall Effect Thrusters only require a single operating point telecommunication satellites and scientific probes will need in the near future versatile electric thrusters capable to realise optimised mission profiles requiring high specific impulse for station keeping or interplanetary segments of scientific missions and high thrust levels for orbit topping/raising or final orbit acquisition [3].

These different kinds of missions require very different, quite antagonistic, optimisations of thruster operations:

- orbit raising missions need a low thrust specific power which require to operate in high mass flow rate, high discharge voltage conditions in order to optimise the ionisation of the working gas

- station keeping or scientific interplanetary missions need a high specific impulse which require to operate at high voltage, low mass flow rate in order to maximise ions acceleration at fixed discharge power.

Even if classical single stage Hall effect thrusters (HET) can operate in a large domain of performances [4, 5], they present optimum performances while operating around nominal points for which both ionisation and acceleration processes are jointly optimised.

To prepare the development of these future versatile thrusters Snecma is currently working on Double Stage Hall Effect Thruster (DSHET). Allowing to optimise independently ionisation and acceleration operations - ionisation is performed in the first stage, while acceleration of ions is achieved in the second stage – this concept appears as very promising for multimode operations. Furthermore, allowing an enhanced ionisation and a better control of ion trajectory this design also appears promising in terms of efficiency improvement and plume divergence reduction.

2. Double stage hall effect thruster concept

Analysis of elementary processes controlling classical single stage HET efficiency reveals that HET's main limitations for multimode operations are related to [4]:

- the decrease of ionisation efficiency at low mass flow rate.
- the strong interconnection between ionisation and acceleration processes

Decrease of the ionisation efficiency can be understood as a consequence of the reduction of the ionisation frequency for a neutral atom at low mass flow rate. At fixed discharge power it defines an upper limit for high voltage operation and therefore for high specific impulse operations. Concerning interconnection issues, even if HET can operate in a large domain of performances their optimisation (including life capabilities) for multi-mode operation is difficult since it is quite impossible to optimise independently ionisation and acceleration processes.

Separating ionisation and acceleration functions, double stage HET intrinsically solves issues related to the interconnection between these operations. In this frame, while the acceleration stage can be advantageously based on a classical HET main challenges for ionisation stage appears to improve the ionisation operation, even at low mass flow rate and to ensure a good control of ion trajectories in order to optimise their injection into the acceleration stage

Different approaches can be proposed to improve the ionisation operation [6]:

- the first one is to reduce the electric power dedicated to ionisation by delivering the required current directly in the ionisation zone [7, 8]
- the second approach consists in reducing the energetic cost required to sustain ionisation by using high frequency discharge (capacitive, inductive, helicon …) [9, 10] or magnetically confined ion sources as ionisation stage [11, 12].

Magnetic field lines in a cold plasma being almost equipotential lines, magnetic ion sources appear as very interesting candidates to meet ionisation stage requirements. Indeed, magnetic confinement of electrons allows to increase their residence time in ionisation stage and therefore to increase ionisation efficiency while the control of electric field geometry through magnetic field topology optimisation makes possible to control the trajectory of created ions. However, the selection of magnetic configuration remains the crucial choice.

In the new proposed DSHET concept [13] plasma confinement in ionisation stage is achieved thanks to a semi Galathea trap [14] generated by a special magnetic arrangement including especially a magnetic coil (called myxina) embedded in the ionisation stage plasma. Acceleration stage is similar to a classical HET. Gas is injected at the rear part of ionisation stage where it is ionised by magnetically confined electrons. By applying few tens volts of potential difference between ionisation stage walls (including myxina walls) and the separatrix (see Figure 1) it is possible to create a potential well where ions are trapped and guided toward the entrance of acceleration stage. As discussed above, electron temperature being relatively low, magnetic field lines are almost equipotential lines. Therefore, fixing the potential on one point of a magnetic line allows to fix the potential all along this line. In this way the depth of the potential well is defined by the potential difference between ionisation stage walls and intermediate electrode which appears as anode of the acceleration stage and cathode of ionisation stage.

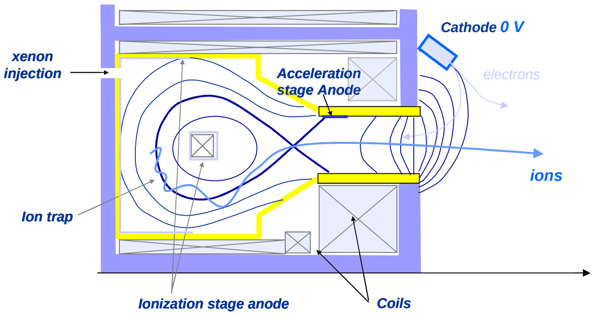

Fig. 1. Schematic of selected DSHET

3. Concept validation

In order to validate experimentally basic features of the presented DSHET concept different prototypes have been manufactured and tested at MIREA laboratory.

3.1.DSHET physical features validation

First activities have been dedicated to the conceptual validation of ionisation stage on a low power (1kW) DSHET. This prototype has been designed in order to allow the characterisation of ionisation stage main plasma parameters (V_p, n_e, T_e) through probes measurements.

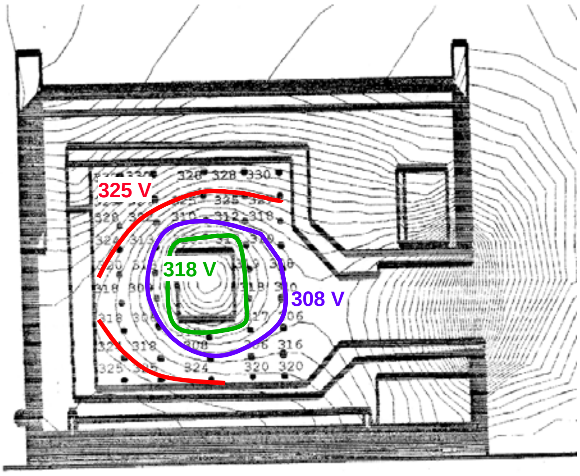

Fig. 2. Plasma potential (V) inside 1kW DSHET's ionisation stage

Thus, cartography of ionisation stage have been performed in MIREA test facility equipped with a diffusion pumping system for $U_{acceleration}$ = 300 V, $U_{ionisation}$ = 50 V, $\dot{m}$ = 2 mg/s [15]. These tests confirmed the main expected characteristics of ionisation stage :

- plasma density distribution inside ionisation stage (Figure 2) exhibits a maximum at the centre of ionisation stage. This is a clear evidence of magnetic confinement efficiency.
- Plasma potential distribution (Figure 3) confirms the establishment of a potential well will allow to control ion trajectories.

Furthermore a good coincidence between electric potential lines and magnetic field lines can be observed. This evidences

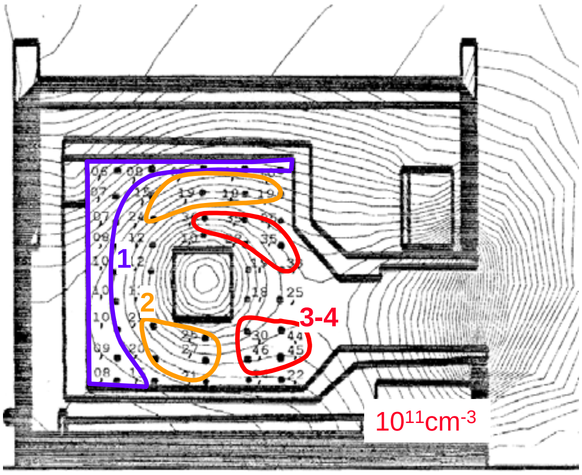

Fig. 3. Plasma density (10^{17} m^{-3}) inside 1kW DSHET's ionisation stage

the small deformation of equipotential lines with respect to magnetic ones. It confirms therefore the possibility to achieved a fine control of electric field configuration through a magnetic field optimisation.

3.2.Performances

Following these first activities on 1kW DSHET demonstrator different prototypes have been manufactured and tested in order to assess functional performances in 1.5kW and 3kW discharge power range and to develop scaling capabilities.

Performances of 3 kW DSHET are presented below as example of concept capabilities in a reference discharge power range. They have been obtained in MIREA test bench. Specific impulse and efficiency values includes cathode mass flow rate but power dissipation in magnetic coils is not taken into account in calculation of efficiency.

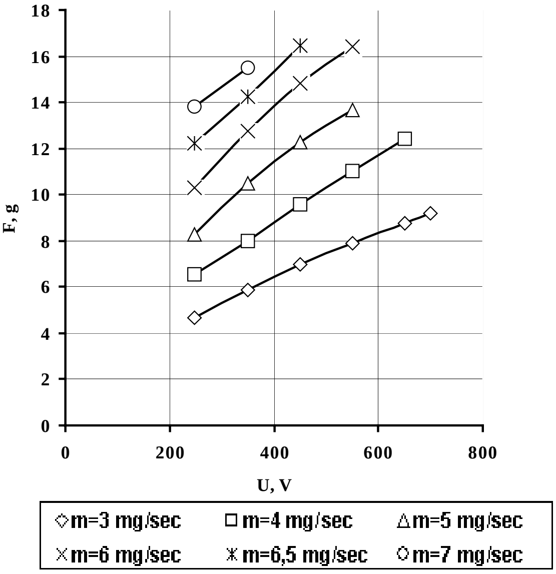

Figure 4 : Thrust vs discharge voltage for different mass flow rates

In addition to these very interesting performances, the narrow plume divergence appears as a promising characteristic of this new concept.

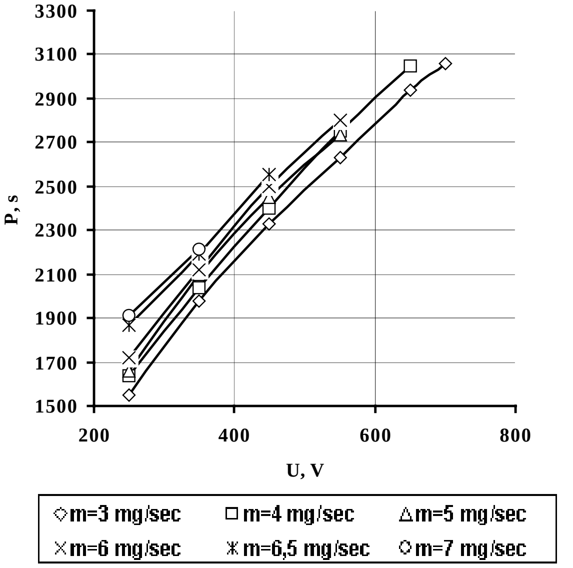

Figure 5 : Specific impulse vs discharge voltage for different mass flow rates

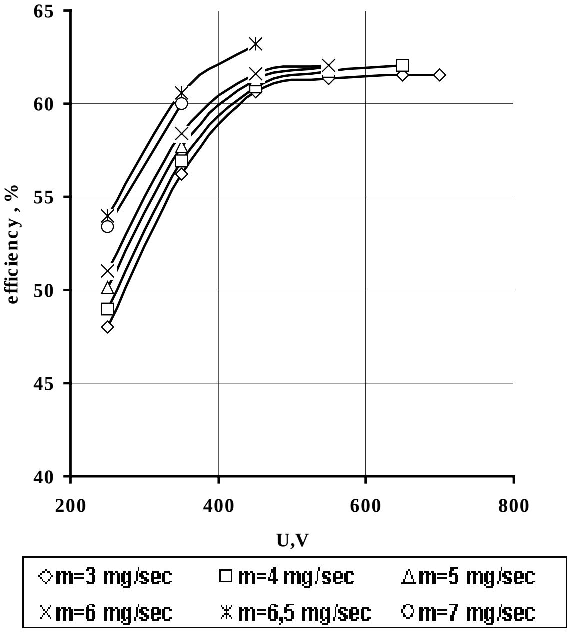

Figure 6 : Discharge efficiency vs discharge voltage for different mass flow rates

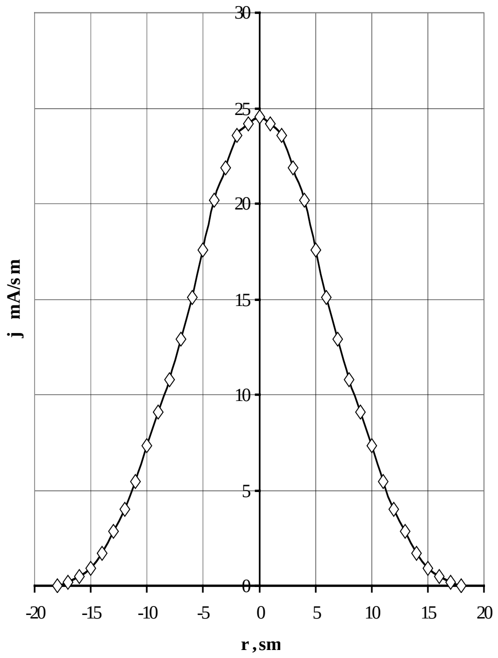

Figure 7 : Ion current radial distribution in the plume

4. Double stage Hall Effect Trhuster modelling

4.1.1. *Functional model of the DSHET*

To analyse the influence of magnetic field on plasma behaviour and therefore to support magnetic circuit design a quasineutral hybrid model similar to the one described in Ref. [16] has been adapted to the DSHET [17].

In this model ions and neutral atoms transport is described with PIC (Particle-In-Cell) simulations while electrons are considered as a fluid and described with momentum equations. The electric potential is deduced from the electron momentum equation where the plasma density is obtained from the simulation of ion transport. Electron energy and ionization rate can either be obtained from fluid equations assuming a Mawellian electron velocity distribution, or from a Monte Carlo simulation of electron trajectories (Figure 8).

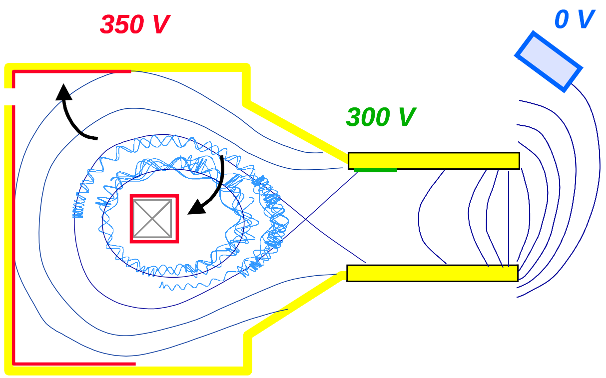

Figure 8 : Example of electron trajectories in ionisation stage calculated by a Monte Carlo simulation

In order to give a correct description of the zero magnetic field area, the hybrid model distinguish four different regions. In each of these regions the electric potential is calculated as described above. The results, displayed in figures 9 to 11, show that the model gives a good qualitative description of DSHET main features, both concerning the magnetic confinement of electrons (Figure 8 and the control of ion trajectories (Figure 10) in the ionisation stage potential well (in Figure 9).

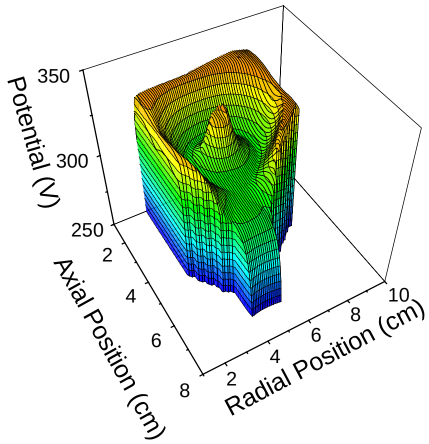

Figure 9 : Example of potential distribution in the DSHET (only part of the channel is represented). The xenon mass flow rate is 2.5 mg/s, the voltage drop in the channel is 300 V and the voltage drop (between the mixina-wall line and the anode of the second stage) in the first stage is 30 V.

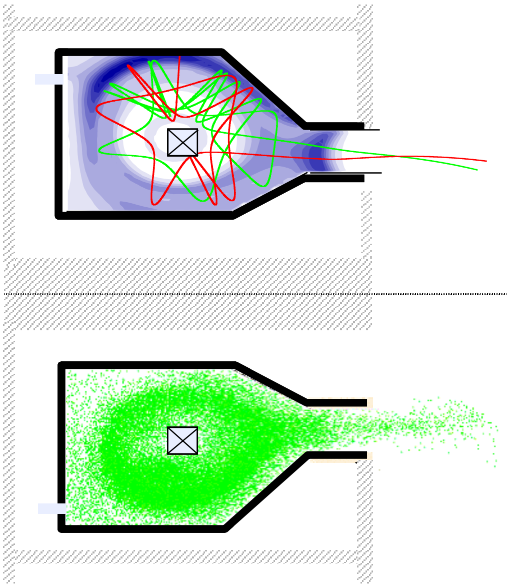

Figure 10 : Calculated ionization rate (10.22 m-3s-1) and an example of ion trajectories (top), and positions of a sample of ions in the simulation.

Although the results predicted by the model seem qualitatively in agreement with the observations, it seems that improvements of the model are necessary to obtain reliable predictions and a clear understanding of the key parameters controlling the operations of the DSHET. Work is continuing to improve the description of the electron kinetics in the ionization chamber (by using an uncoupled, Monte Carlo simulation of electron transport in the ionization chamber) and to find a better way to obtain the potential distribution.

5. Conclusion

Double Stage Hall Effect Thruster appears as a very promising concept in order to improve both thruster's versatility and performances.

First fundamental physical studies confirm these trends and allow to validate basic physical features associated with magnetically confined ionisation stage.

Tests of 1.5 and 3kW prototypes in cryogenic vacuum conditions should allow to confirm these promising characteristics soon.

Acknoledgment

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References

[1] Koppel C.R., Marchandise F., Estublier D., Jolivet L., ‘ The SMART-1 electric propulsion system in-flight experience’ AIAA-2004-3435. Submitted

[2] Estublier D., Koppel C., Lyszyk M., Bourguignon E. Miligan D. Darnon F., ‘SMART-1 Electric Propulsion flight experience : main working group findings’, 4th ISPC, Cagliari, Sardinia (2004).

[3] Chesta E. et al., ‘Flexible Variable-Specific Impulse electric propulsion systems for planetary missions’, 5th IAA International Conference on low-cost planetary mission, ESA SP-542, 2003.

[4] Prioul M. et al., ‘ PPS1350qualification status and performances’, 4th ISPC, Cagliari, Sardinia (2004).

[5] Duchemin O., Dumazert P., Estublier D., Darnon F., ‘Testing the PPS®X000 plasma thruster at high discharge voltage’, 4th ISPC, Cagliari, Sardinia (2004)

[6] Prioul M., ‘Double Stage Hall Effect Thruster concept and technology assessment’, Snecma Moteurs technical note to ESA , RT-DSHET-NT-0001-SN-(01) (2003)

[7] Fish N.J., Raitses Y., Litvak A.A., Dorf L.A., ‘Design and operation of Hall Thruster with segmented electrodes’, AIAA 99-2572, AIAA Joint Propulsion Conference (1999).

[8] Gallardo J.M., Ahedo E., ‘Effects of an intermediate electrode on the Hall thruster discharge’, AIAA 2002-4112, AIAA Joint Propulsion Conference (2002).

[9] Leiter H.J, Löb H.W., Schartner H.W., ‘The RIT15 Ion Engines – A Survey of the present state of Radio-frequency ion thruster technology and its future potentiality. 3rd International Conference on Spacecraft Propulsion, ESA SP-465.

[10] Boswell R.W., ‘Plasma production using a standing helicon wave(, Phys. Lett., vol. 33 A, p 457 (1970).

[11] Beal B.E., Gallimore A.D., ‘Development of the Linear Gridless Ion Thruster’, AIAA 2001-3646, 37th Joint Priopulsion Conference Exhibit, Salt Lake City (2001).

[12] Sovey J.S., ‘Improved Ion Containment Using a Ring-Cusp Ion Thruster’, Journal of Soacecraft, Vol. 21, n° 5, p 488-495 (1984).

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[13] Secheresse O., Bugrova A., Morozov A., Snecma Patent 03 08384, filled 9 July 2003.

[14] Morozov A., Savel'ev, 'On Galatheas magnetic traps with plasma-embedded conductors, Physics Uspekhi 41 1049 (1998).

[15] MIREA technical report for Snecma Moteur(2002)

[16] G.J. M. Hagelaar, J. Bareilles, L. Garrigues, and J.-P. Boeuf, "*Two-dimensional model of a stationary plasma thruster*", J. Appl. Phys. 91, 5592 (2002)

[17] Boniface C., Hagelaar G., Garrigues L., Bœuf J.P., 'Hybrid simulation of 3kW Double Stage Hall Effect Thruster', CPAT report for Snecma Moteurs, (30 November 2003).