CHARACTERIZATION OF PLASMA INSIDE THE SPT-50 CHANNEL BY ELECTROSTATIC PROBES

G. Guerrini, C. Michaut, M. Dudeck*, A.N. Vesselovzorov** and M. Bacal

Laboratoire de Physique des Milieux Ionisés, Laboratoire du C.N.R.S
Ecole Polytechnique, 91128 Palaiseau Cedex, France
phone : +33 1 69 33 41 15, fax : +33 1 69 33 30 23

* Laboratoire d'Aérothermique, Meudon and Université Paris 6, France
** RCC Kurchatov Institute, Moscow, Russia

ABSTRACT

A large scientific research program on ion thrusters is developped in France. This work is supported in the frame of a French research program on the electric propulsion in *Groupement de Recherche "Propulsion à Plasma pour Systèmes Orbitaux"* involving laboratories of CNES, CNRS, SEP and ONERA. The main advantages of the Hall-type Thruster are the level of thrust, the energetic characteristics and an acceptable liftetime.

A laboratory SPT Thruster (SPT-50) has been tested in our facility. We show the plasma parameter evolution along the channel axis such as electron temperature, ion density, the space potential and the floating potential. We determine, also, the electron energy distribution functions and the electric field. These measurements have been performed with electrostatic probes. We have determined three different zones inside the channel corresponding to three different discharge phenomena.

NOMENCLATURE

U_d	discharge voltage, V
I_i/I_d	electric efficiency
V_i	ion speed, m/s
I_d	discharge current, mA
$I_i/I_{m'}$	degree of ionization
I_i	ion current, mA
e	electron charge, C
$I_{m'}$	flow rate current, mA
M	ion mass, kg
I_M	coils current, A
V_p	plasma potential, V
ε	electron energy, eV
r_p	probe radius, m
r_L	Larmor radius, m
V_s	probe potential, V

INTRODUCTION

The performances of Stationary Plasma Thruster (SPT) are well-adapted to geostationary telecommunication satellite North/South (or East/West) station keeping. Although the SPT-100 class is generally studied, a series of small closed electron drift thrusters is investigated. In particular, we have studied three small ion thrusters : SPT-20[1,2,3], A3[4] (external diameter : 60 mm) and SPT-50[5].

The SPT-50 is a small Hall-type thruster designed and manufactured by the RCC Kurchatov Institute and is currently being investigated in the Laboratoire de Physique des Milieux Ionisés (France) as part of the effort to develop and to contribute to the understanding of the different physical effects in the small ion thrusters. The tests have been performed in the test facility PAVOT (Propulsion Appliquée aux Vols en Orbite Terrestre) of PMI Laboratory (Ecole Polytechnique).

THE EXPERIMENTAL STATIONARY PLASMA THRUSTER AND THE TEST FACILITY

Figure 1 shows schematically the experimental Hall-type stationary plasma thruster SPT-50. The insulated channel is made of boron nitride with an external diameter of 50 mm and an internal diameter of 28 mm. At the bottom of the channel, a small ceramic chamber is used to uniformize the xenon injection. The gas inlet system is separated from the anode. The ring-shaped anode is mounted at 25 mm from the channel exit. The inside surface of the cold hollow cathode is covered by LaB_6. Xenon is used as working gas with a mass flow rate in the range 0.8-1.5 mg/s. The hollow cathode used in PAVOT facility operates with a xenon flow rate in the range of 0.05-0.1 cm^3/s, i.e., 1/3 of the flow rate injected in the thruster. The magnetic circuit of the SPT-50 consists of an inner coil and four discrete external coils providing easy access to perform measurements in the chamel.

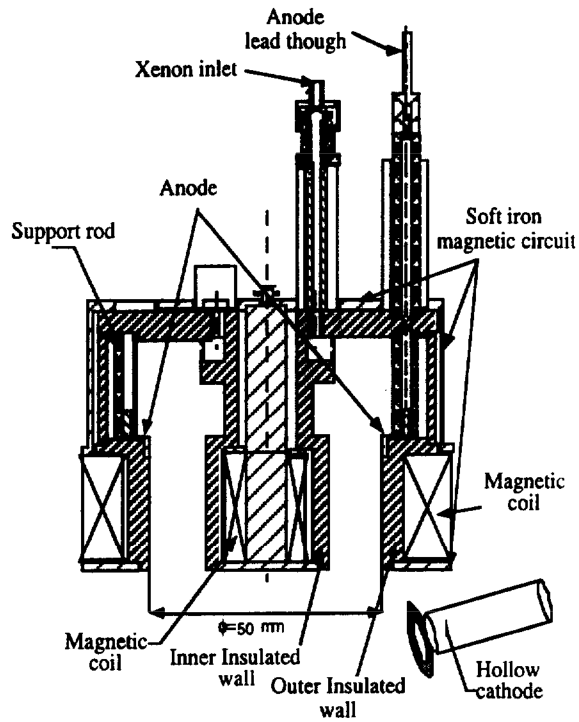

Figure 1 : The schematic representation of the Hall-type thruster SPT-50.

The test facility at PMI Laboratory consists of a horizontal, cylindrical stainless steel vacuum chamber pumped with a cryogenic pump with a pumping speed of ~5000 l/s. Its size is 1.80 m in length and 0.80 m in diameter (900 l in volume) (Figure 2). Such dimensions are chosen to avoid significant xenon beam-wall interactions. Most of investigations were made at a chamber pressure of (5-8)x10^{-5} mbar, for a flow rate inside the channel of 0.17 cm^3/s (~1 mg/s).

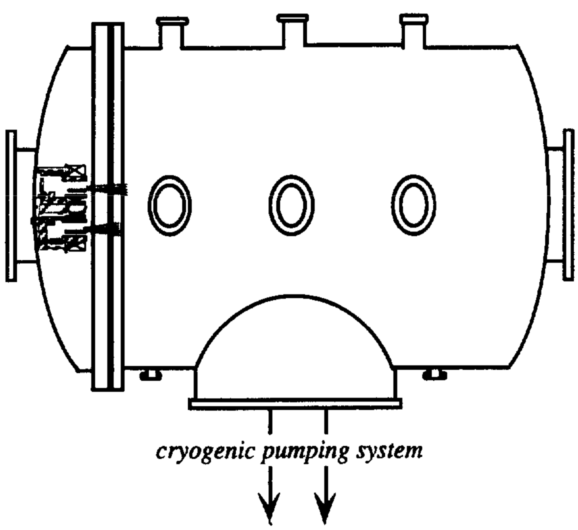

Figure 2 : Schematic view of the test facility PAVOT.

SPT-50 CHARACTERISTICS

The magnetic field has been studied inside the channel. These measurements have been performed with a Hall probe having an area of 4 mm^2. Figure 3 shows the profiles of the magnetic field for two different coil currents.

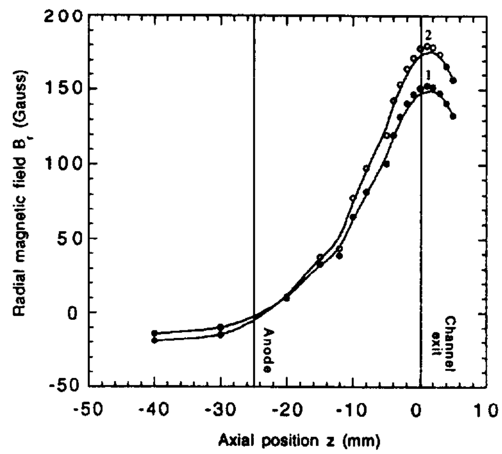

Figure 3 : Distribution of the radial magnetic field inside the channel. $I_m$int, $I_m$ext (A) : 1) 1,4 - 2,8 A. 2) 2 - 4 A

Profiles of the radial magnetic field are the same as in larger thrusters[6]. The magnetic field is equal to zero near the anode and is maximum at the channel exit : 180 Gauss with coil currents equal to 4 and 2 A (external and internal coil, respectively).

Figure 4 shows that at similar voltage and working pressure, the results obtained in SPT-50 are similar to those obtained in larger thrusters such as SPT-100. The dependence of the discharge voltage, U_d, of the discharge current I_d, the ion current I_i, the electric efficiency I_i/I_d and the degree of ionization I_i/I_m' is shown on Figure 4.

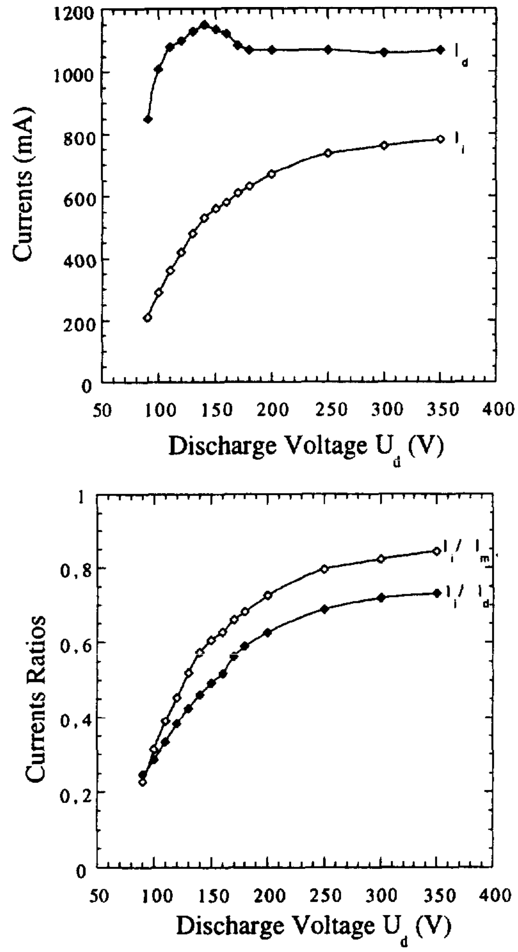

Figure 4 : Effect of discharge voltage on the discharge current, I_d, the ion current I_i, the electric efficiency I_i/I_d and the degree of ionisation I_i/I_m'. The xenon gas flow is 1.07 mgs^{-1} in the anode and 0.34 mgs^{-1} in the cathode. The internal coil current is 2.1 A, the external coil current is 4.2 A.

Figure 4 shows that the discharge current increases with discharge voltage until 140 V, then decreases to a saturation value of 1100 mA. This corresponds to an evolution of the shape of the plume. That means Xenon atoms are almost fully ionized. This is also shown by the degree of ionization reaching 0.95 at a discharge voltage of 350 V. The ion current increases more slowly with discharge voltage. This ion current behavior has been discussed only from a theoretical point of view in an earlier work[7].

PROBE DIAGNOSTICS

Several small openings have been made on the outer insulating wall of the thruster to insert diagnostics, such as electrostatic probe. A series of 6 holes is made along the channel for wall probes. Each hole has a minimum diameter of 0.6 mm and is 7 mm long. The Langmuir probes are cylindrical (0.5 mm diameter) and made of Tantalum. The probes are distant 4 mm from each other. A seventh probe has been added at 1 mm from the channel exit. This probe is also in Tantalum. The wall probes exit of the wall surface by less than 1 mm.

Another Tantalium probe has been added on the axis of the channel. It has an axial mouvement permitting to determine the profiles of plasma parameters along the channel. This probe is similar to the others with a diameter of 0.5 mm and a length of 1 mm. This probe is called "moving" probe. This setting is shown on Figure 5.

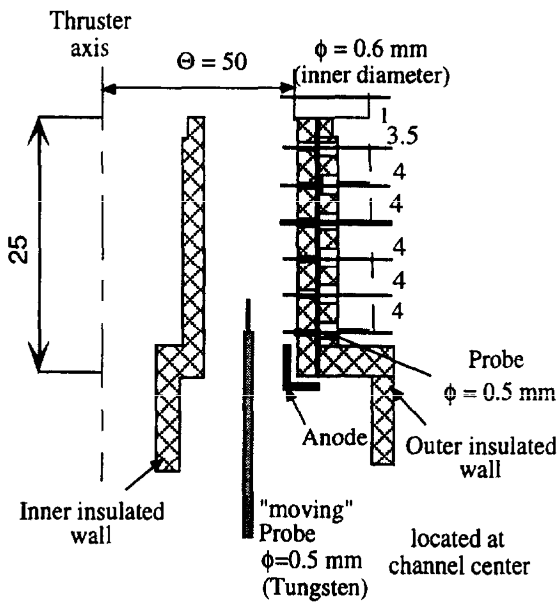

Figure 5 : Experimental setting of electrostatic probes inside the SPT-50 thruster.

EXPERIMENTAL RESULTS

We have studied plasma parameter profiles along the channel for different discharge voltages. The xenon flow rate is constant at 0.20 cm^3/s. Coil currents are chosen to obtain a minimum discharge current. The results for plasma potential and axial electric field are presented on figure 6. The electric field is obtained from the first derivative of plasma potential. For each discharge voltage, plasma potential is constant on 17 mm from the anode. Then it decreases to attain around 70 V at the channel exit. Maximum values of the electric field correspond to the high decrease of plasma potential at z=17 mm. Figure 7 shows the profiles of electron temperature, ion current and ion density along the channel. The ion current is obtained from the linear extrapolation of the ion branch to the plasma potential. We used the ion velocity, defined as $V_i = \sqrt{\frac{2e\left(U_d - V_p\right)}{M}}$, in order to determine the ion densities.

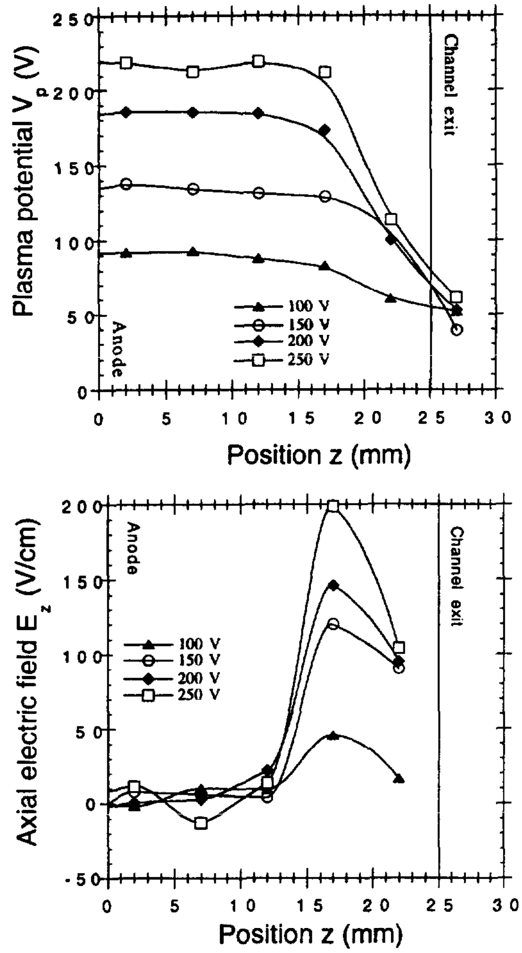

Figure 6 : Plasma potential and electric field profiles inside the SPT-50 channel obtained with the "moving" probe for different discharge voltages. Xenon flow rate is constant at 0.20 cm^3/s.

We observe on figure 7, that the electron temperature increases from z=12 mm from the anode to attain maximum values at z=17 mm. The maximum values increase with discharge voltage. For 250 V of discharge voltage, the electron temperature is equal to 30 eV. Ion currents and ion densities increase along the channel for any discharge voltage. The ion current attains 10 mA at 1 mm from the channel exit for 250 V of discharge voltage. At the same location and for 250 V, the ion density is equal to 2.5×10^{12} cm^{-3}.

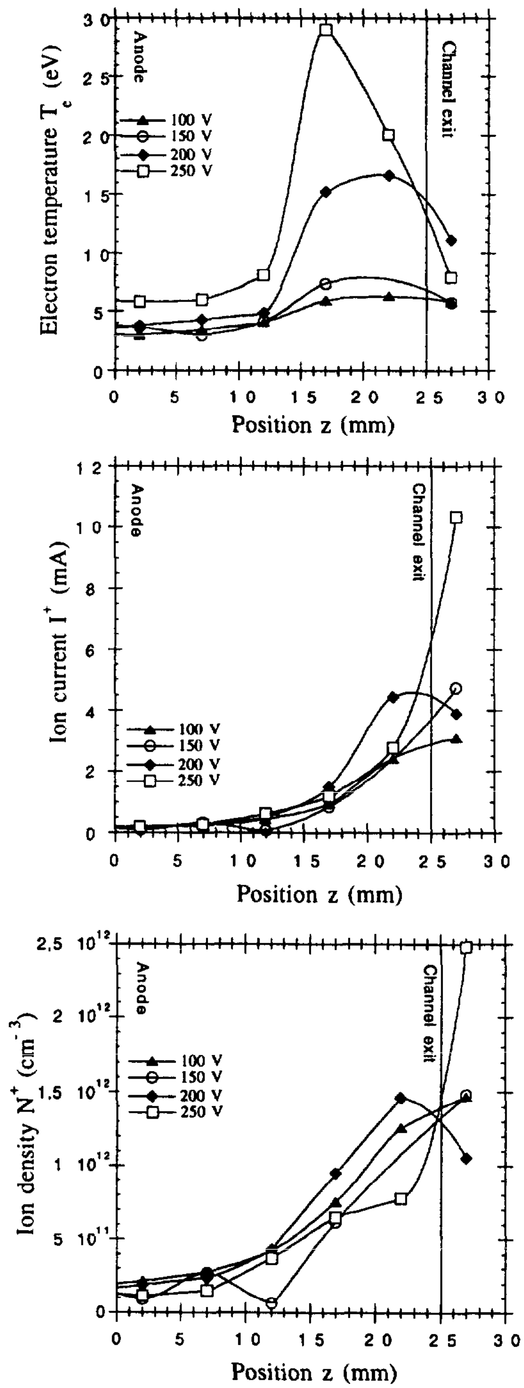

Figure 7 : Electron temperature, ion current and ion density profiles inside the SPT-50 channel obtained with the "moving" probe for different discharge voltages. Xenon flow rate is constant at 0.20 cm^3/s.

Finally, we have studied the degree of ionization, $I_i/I_{m'}$, along the channel (figure 8). It increases along the channel but inside the channel it is constant with discharge voltage.

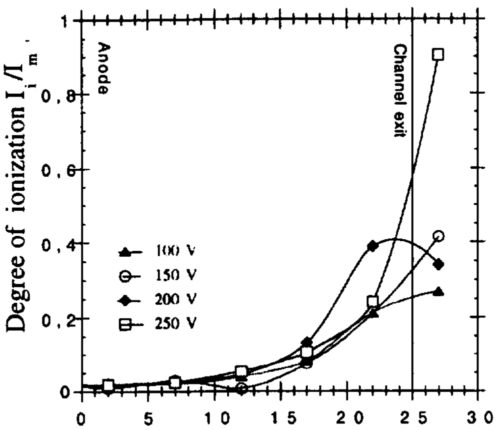

Figure 8 : Profiles of degree of ionization along the channel for different discharge voltages.

It appears that three main regions exist inside the channel. First, from the anode to z=12 mm. Electron temperature is low (~5 eV), ion current and ion density are weak and the plasma potential is high. There is a large part of Xenon atoms in this region (degree of ionization ~0.05 - 0.15). Due to this weak ionization, this region is called "pre-ionization" zone where the plasma is stable.

Then, all plasma parameters (except plasma potential) increase from z=12 mm to z=17 mm. In this region, Xenon atoms are ionized by electrons coming from the hollow cathode. Plasma potential is constant and high until z=17 mm. Thus, the electric field is low and constant, the ions are not accelerated. This region is called "ionization" zone. In this region, the electron temperature is high enough to ionize partially or totally the gas (it depends on discharge voltage).

Finally, there is a third region called "acceleration" zone. The ion density and the electric field are high (200 V/cm for 250 V of discharge voltage). Ions are accelerated to the channel exit. Their transit time in this zone is low. It results in a decrease of ion density close to the channel exit. The degree of ionization continues to increase. For 250 V of discharge, I_i/I_m, is equal to 0.9 near the exit.

ELECTRON ENERGY DISTRIBUTION FUNCTION

From the results obtained with electrostatic probes, we have determined the Electron Energy Distribution Function (EEDF) inside the channel. The measurements were made at z=0 (anode), 10, 15, 20 and 25 mm (channel exit). The radial position is r=20 mm corresponding to the channel center.

The classical theory[8] shows that probe measurements in a magnetic field are possible only if the probe radius satisfies the relation $r_p \leq r_L$. Under running conditions for SPT-50 the Debye radius satisfies $r_D < r_L$ but the difference between the two radii is not large (r_D/r_L~0.2 - 0.5).

Earlier work[9] has shown that probes satisfying the condition $r_p \leq r_L$ cause weak perturbations of ±2 V on the plasma potential. We note that plasma potential in the channel is around 180 V. In our results, we have neglected the magnetic field effect.

We have determined the EEDF inside the channel by the Druyvesteyn method[10]. From the probe characteristics by differentiating twice, if the EDDF, F(ε), depends of only one argument, we can write :

$$F(\varepsilon) = \sqrt{\varepsilon} f(\varepsilon)$$

$$\text{with } f(\varepsilon) = \frac{2\sqrt{2 m_e}}{e^3 S} \cdot \frac{d^2 I}{dV^2}(V)$$

$$\text{and } \quad \varepsilon = -e(V_s - V_p)$$

We have studied the EEDF profiles versus the position in the channel, the discharge voltage and the xenon flow rate. The "moving" probe has been shifted from z=0 (anode) to z=25 mm corresponding to the channel exit (figure 9).

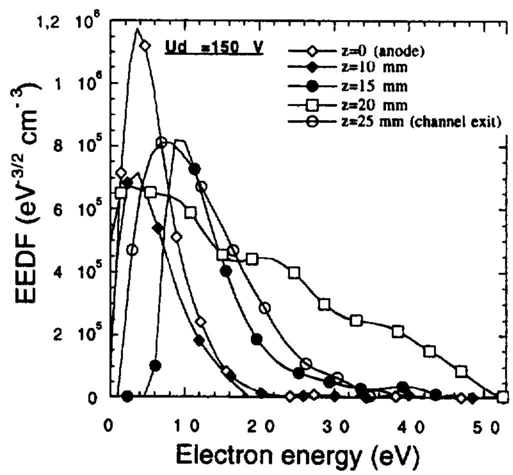

Figure 9 : EEDF inside the channel obtained with the "moving" probe at different position in the channel. The discharge voltage is 150 V and the Xenon flow rate is 0.17 cm^3s^{-1}.

Near the anode ("pre-ionization" zone) and at the channel exit (acceleration zone), we observed one single electron population between 0 and 40 eV. On the other hand, for z=20 mm corresponding to the "ionization" region, three electron populations are observed : from 0 to 20 eV, from 20 to 35 eV and from 35 to 55 eV. Note that the highest amplitude is for the EEDF in the "pre-ionization" region.

We have studied the discharge voltage effect on EEDF (figure 10). The discharge voltage varies between 100 to 250 V. The studied region is the "pre-ionization" zone (z=10 mm, where a single electron population is observed).

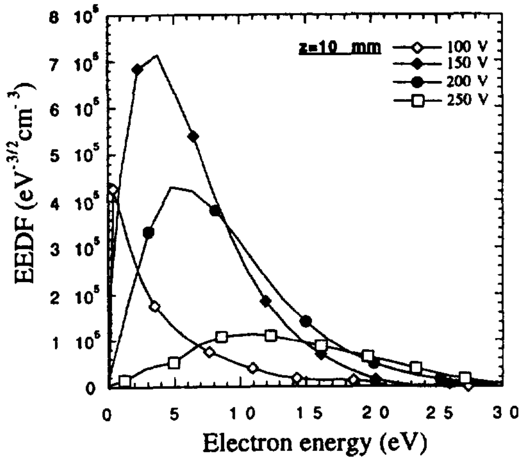

Figure 10 : Effect of the discharge voltage on EEDF inside the channel for z=10 mm ("pre-ionization" region).

We observed that EEDF is maximum for 150 V of discharge voltage. Then it decreases. This discharge voltage corresponds to the maximum of discharge current (figure 4).

We noted that the Xenon flow rate in thrusters has an important effect on plasma parameters. From probe characteristics obtained versus the gas flow rate, we have determined the EEDF (figure 11). The discharge voltage is kept constant at 200 V and the gas flow rate in the channel varies between 0.14 and 0.25 cm^3/s (~0.8-1.5 mg/s). The measurements have been performed for z=0 (anode) and z=17 mm ("ionization" zone).

Figure 11 shows that the Xenon flow rate has a weak influence on EEDF. We notice for z=0 a single population with a maximum for a flow rate of 0.17 cm^3/s. Then, the EEDF amplitude decreases with flow rate. Also, we note that for a gas flow rate higher than 0.2 cm^3/s, the EEDF is constant. This observation is also valid for z=17 mm ("ionization" region) where we notice three electron populations whatever the gas flow rate. It appears a flow rate limit value because the EEDF behaviour is different depending on whether flow rate is higher or lower than 0.17 cm^3/s. At this flow rate, the third population of "fast" electrons is very weak.

When the flow rate increases above 0.17 cm^3/s, the average electron energy decreases. The neutral particle flux is more important involving that electrons, coming from the hollow cathode and accelerated by the electric field, have more collisions with these neutrals.

We have seen that two different EEDF appear inside the channel. First, near the anode and close to the channel exit, there is a single electron population with energies varying between 0 and 30 eV. On the other hand, in the "ionization" zone, we have observed three electron populations.

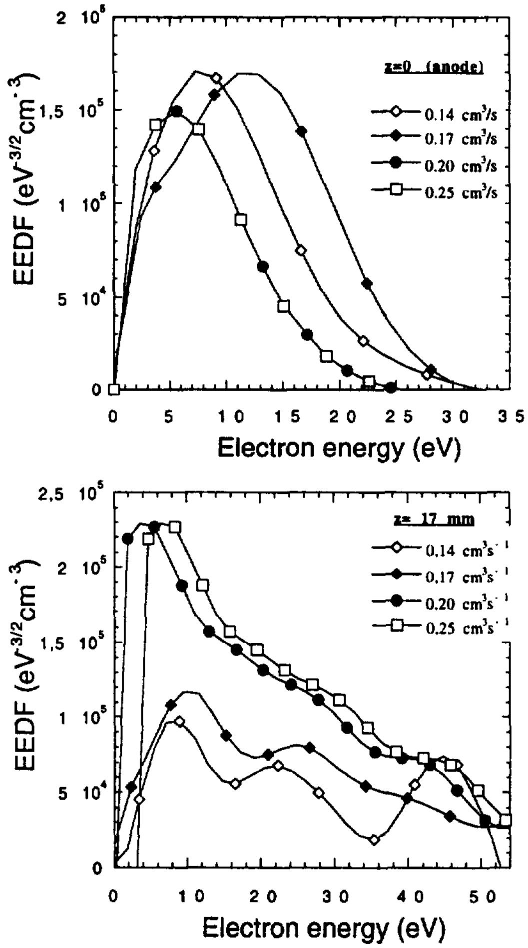

Figure 11 : Effect of the Xenon flow rate on EEDF inside the channel for z=0 ("pre-ionization" region) and z=17 mm ("ionization" region).

We noted the disappearance of the "fast" electron and the intermediate electron population near the anode. Without plasma inside the channel, electrons emitted from the hollow cathode (~20 eV) would be accelerated by the axial electric field through the channel. These electrons swould have an energy close to the discharge voltage. By collisions, electrons with a high or an intermediate energy loose their energy to ionize the gas. The observed electrons in the "pre-ionization" zone have a weak energy (~20 eV).

The electron dynamics is very complicated inside the channel because, in this configuration, the magnetic field lines are perpendicular to the channel insulated walls and the main part of electrons reach these walls. Secondary electron emission plays an important part in the EEDF shape (in particular in the intermediate electron population).

We have also studied the EEDF using the probes located near the walls (figure 12). We obtained EEDF for three locations inside the channel : z=5.5 mm ("pre-ionization" region), z=13.5 mm ("ionization" region) and z=21.5 mm ("acceleration" region). The discharge voltage was 250 V and the Xenon flow rate inside the channel was 0.17 cm^3/s (1 mg/s).

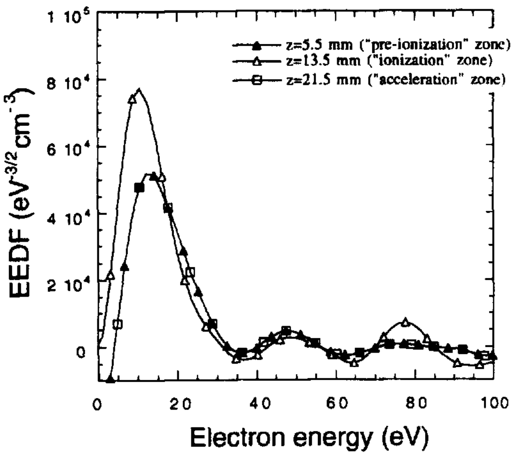

Figure 12 : axial profiles of EEDF close to the walls for three locations inside the channel.

The three electron populations are observed near the wall whatever the location. Electron energies are higher than on the channel axis. "Cold" electron population energy varies between 0 and 35 eV, the intermediate electron population energy between 35 and 65 eV and for the "fast" electron population energy between 65 and 90 eV. But in the "pre-ionization" zone and the "acceleration" zone, the third population is very weak.

CONCLUSION

We have seen that three main regions are found inside the channel :

• From the anode to z=11.5 mm, a pre-ionization region where the ionization degree and the ion current are weak and where the plasma potential is high.

• From z=11.5 mm to z=18 mm, the plasma potential decreases, the degree of ionization and the ion current increase and the electron temperature is large. This is the ionization region.

• Then, from z=18 mm to the channel exit, the plasma potential quickly decreases and the ion current increases. The ions are accelerated by the axial electric field present in the channel. This is the acceleration region.

For each region, the Electron Energy Distribution Function is different. In the pre-ionization and acceleration regions, we have observed, on the channel axis, one single electron population with low energies (0-40 eV). In the ionization zone, we have observed three electron populations with energies from 0 to 60 eV.

These three populations can be explain as follows :

• Electrons emitted from the hollow cathode are accelerated by the axial electric field. This population represents the "fast" electron population (35 - 60 eV).

• We have seen that a part of electrons reaches the walls. The intermediate electron population can be explained as the secondary electron emission from the walls. Their energies vary between 15 - 35 eV.

• Finally, the third electron population comes from the Xenon ionization or from the electron energy loss for the ionization. Their energies vary between 0 and 15 eV.

Acknowledgements. We gratefully acknowledge CNES for the financial support of this work. Also, one of us, G.G., acknowledges the fellowship provided by CNES and SEP.

REFERENCES

[1] G. Guerrini, A.N. Vesselovzorov, M. Bacal and I.B. Pokrovsky, Rev. Sci. Instrum., 67, March 1996, p. 990-992.

[2] G. Guerrini, A.N. Vesselovzorov and M. Bacal, 24th International Electric Propulsion Conference, vol. 1, p.259, IEPC-95-32, Moscow (Russia), September 1995.

[3] G. Guerrini, C. Michaut, A.N. Nikitin, A.N. Vesselovzorov and M. Bacal, Proceedings od the thirteen's ESCAMPIG, Poprad (Slovaquia) 27-30, August 1996, vol. 20E, Part A, p. 207.

[4] G. Guerrini, C. Michaut, M. Dudeck and M. Bacal, 2nd European Spacecraft Propulsion Conference, ESTEC, Noordwijk (Holland), 27-29 May 1997.

[5] G. Guerrini, C. Michaut, A.N. Vesselovzorov, M. Dudeck and M. Bacal, Proc. 23rd ICPIG, Toulouse (France), 17-22, July 1997.

[6] S.N. Askhabov, I.V. Melikov and V.V. Fishgoit, Sov. Phys. Tech. Phys., 22, **4**, 453 (1977).

[7] T. Randolph, M. Day, V. Kim, H. Kaufman, V. Zhurin, K. Kozubsky, 23rd International Electric Propulsion Conference, Seattle, WA, September 13-16, 1993, paper IEPC-93-093.

[8] I. Langmuir and H. Mott-Smith, General Electric Rev., 27, 449 (1924).

[9] V.S. Versotskii and V.T. Niskin, 6th All-Union Conf. on Plasma Accelerators and Ion Injectors, Dnepropetrovsk (1986).

[10] M. Druyvesteyn, Z. Phys., **64**, 781 (1930).