Transitional regime in the start-up process of conventional Hall thrusters

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The operation of conventional Hall thrusters in laboratory experiments shows an anomalous start transient characterized by an increase of the discharge current along several minutes. In this study we correlate the appearance of the transitional regime with the presence of gas impurities within the thruster, which is previously exposed to the atmosphere. Water, Nitrogen, and Hydrogen seem to be the most important residual traces responsible of the phenomena. The physical mechanisms behind the transitional regime are studied through different experiments, and the results show the relevant role of the plasma-wall interaction.

I. Introduction

Experimental results at the Hall Thruster Experiment (HTX) facility in the Princeton Plasma Physics Laboratory show that there is a transitional regime in the start-up process of a conventional Hall thruster.[1–5] The transitional regime is characterized by an increase of the discharge current (more than 20% over the stationary current) along 15-30 minutes, and is present in a wide range of conditions. Usually, these first minutes of operation of the thruster are not 'considered' in laboratory experiments since certain time is required to work properly in vacuum conditions.

There is not evidence to exclude the transitional regime in space missions. And this transitional regime can be very important in certain missions where short duration firings of the thruster are requiered or there is a rapid deployment of the thruster after the launch. Moreover, recent studies analyze the viability of low earth orbits using Hall thrusters, where the environmental exposure can be relevant for the transitional regime.

This work studies, through several experiments and theoretical considerations, the main physical mechanisms involved in the transitional regime. First, it is shown that the presence of gas impurities inside the thruster (Water, Hydrogen, Nitrogen) can be correlated with the increase of the discharge current, even in a re-start up process. Moreover, the transitional regime persists until the purge of the thruster is done. Second, the location and diffusion of these impurities are analyzed, showing that the chamber walls of the thruster are the most likely suspects, whereas the experimental facility has a marginal effect. And third, the plasma-wall interaction is postulated as the main process that changes the discharge current in the transitional regime. Other possible processes such as the higher electron conductivity by collisions or the higher ion current by the ionization of gas impurities are also studied.

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II. Experiments

The experiments were made at the HTX facility in the Princeton Plasma Physics Laboratory. A detailed description of the facility and the 2kW Hall thruster used for experiments can be found in reference.[6] Nevertheless we highlight the most relevant characteristics.

The vacuum facility consists of a 2.3 m diameter by 8.4 m long vacuum vessel of stainless steel walls and three CVI cryogenic pumps including two CVI TMP1000 mounted on two vacuum vessel ports downstream of the thruster and one CVI TM 1200i mounted internally behind the thruster. They provide a total measured pumping speed about 90000 l/s with Xenon flow. The base pressure was $2-3\cdot10^{-8}$ torr, and with the Xenon flow rate of 21 sccm, the backgound gas pressure did not exceed 3 microtorr. The pressure measurements were conducted using nude ion gauges without the thruster operation. The gas flow was controlled by gas flow controllers FC-260 calibrated both by the manufacturer (Millipore Corp.) and in-house by a volumetric method prior to operation.

The 2kW Hall thruster used in the experiments has a modular design and consists of a coaxial channel made from boron nitride grade HP ceramic material, which can also include segments of different ceramic and conductive materials, magnetic circuit, and the anode, which is also a gas distributor. The dimensions of the thruster channel are: outer diameter, 123 mm, inner diameter, 73 mm, channel length, 46 mm, thickness of the outer wall, 6 mm, and thikness of the inner wall, 4 mm. The magnetic field is controlled by magnetic screens and additional electromagnetic coils that are supplied by separate power supplies. The main power supply that support the thruster operation is the 1kV-10A BRC-1000 model by Universal Voltronics. A Heatwave thermionic hollow cathode is used as cathode-neutraizer.

The Hall thruster is operated with Xenon gas in the input power range of 0.5 to 3.5 kW. The nominal conditions of operation are: discharge voltage, 250 V, anode mass flow, 19.4 sccm, and cathode mass flow, 2 sccm. The start-up procedure of the thruster consist of the following steps. Once the base pressure is achieved in the vacuum vessel, Xenon gas is injected in nominal conditions, and the cathode heater is turned on (23 A). The initiation of the cathode discharge is facilitated by the keeper electrode biased 50 V with respect to the cathode emitter. When the plasma discharge begins, the cathode keeper and heater are turned off and the discharge current is self-sustained.

The diagnostic setup consists of fast and slow movable probes for plasma measurements inside the thruster and a high precision rotating system for plume diagnostics, which includes, among other diagnostic tools, a flat electrostatic probe with a guarding sleve and a 45° two-plate energy analyzer. The plume diagnostics setup determines the total ion flux and the ion energy distribution along the probe angle relative to the physical centerline. Uncertainties in the determination of the total ion flux are taken into account in the posterior computations.

A. Transitional regime

The observed transitional regime is characterized by the following facts. At the begining of the operation of the thruster, the discharge current is close to the nominal current, but shortly after it raises quickly to a maximum value, which can be a 20-40 % over the nominal one. Then the discharge current I_d decreases in a similar way, thus defining a *peak* in the discharge current evolution. This I_d-peak takes place in a time period of 15-30 minutes. After this peak, the discharge current decreases slowly to the stationary value, $I_d(\infty) = 1.68$ A, in approximately 1-2 hours. Along this time, the discharge current presents a very low frequency mode of oscillation of the order below 1 mHz.

The behavior of the transitional regime is repeatable in a wide range of conditions. Despite the qualitative properties are almost the same in all cases, the magnitudes of the transitional regime can be quite different depending on the design of the thruster, the wall materials, and the thruster operation conditions. We analize two hypothesis for the transitional regime, both related to the working gas of the thruster. The first one is that trapped Xenon is coming from walls, since experimental results[7] show that Boron Nitride (BN) has the capacity to capture and release it. To estimate the total amount of trapped Xenon in the ceramic walls, $\Delta M_{tp.Xe}$, we use the formula,

$$\Delta M_{tp.Xe} = \rho C_{ref}\frac{AM_{Xe}}{AM_{BN}}\int\limits_{i.wall+o.wall} y dV \simeq 6\pi L(R_i+R_o)\rho\frac{AM_{Xe}}{AM_{BN}}C_{ref}\lambda, \tag{1}$$

where ρ is the density of BN, AM_{Xe} and AM_{BN} are the atomic masses of Xenon and BN, respectively, L is the length of the channel of the thruster, R_i and R_o are the inner and outer radius of the thruster, respectively, and $y = C/C_{ref}$ is given in figure 1 and represents the dimensionless concentration of Xenon inside the ceramic, with $C_{ref} = 0.0074$ a reference value of the xenon concentration and $\lambda = 80$ nm the characteristic length of penetration. A simple estimation shows that only about 1 mg of Xenon can be trapped in the ceramic walls, which is insufficient to explain the characteristics of the I_d-peak, including the time duration and the amplitude of the discharge current. In addition, the Xenon pressure along the transitional regime did not vary significantly in the experiments. Therefore, we reject this hypothesis.

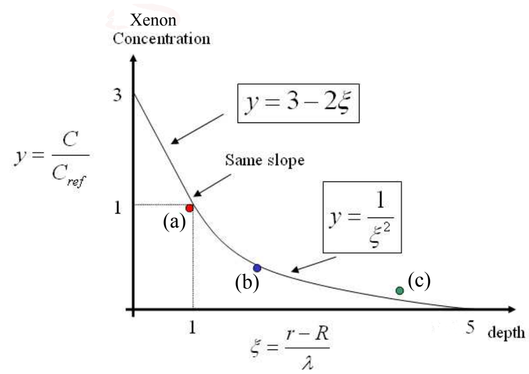


Figure 1. Dimensionless concentration of Xenon inside the boron nitride walls of the thruster. Reference parameters are: $C_{ref} = 0.0074$ and $\lambda = 80$ nm. Dots in the figure represent experimental values from reference:[7] (a) $y = 1$ and $\xi = 1$, (b) $y = 0.2568$ and $\xi = 2$, and (c) $y = 0.1622$ and $\xi = 4.25$.

The second hypothesis is that there are gas impurities in the working gas that modify the thruster discharge. We measured the residual gas traces of the exhaust stream of the thruster using a mass spectrometer, SRS residual gas analyzer RGA-300 (300 a.m.u). Table 1 summarizes the measured composition of all residual gases in the vacuum vessel. Hereafter we will refer to the residual gas traces as *impurities*.

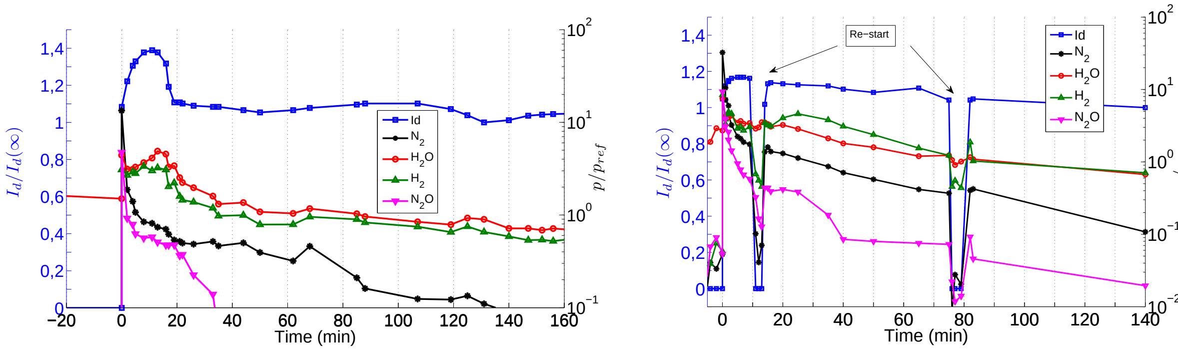
Mass (a.m.u)	Gas
2	H_2
16	O, NH_2
18	H_2O
28	N_2, B_2H_6
44	CO_2, N_2O

Table 1. Most important values of the composition of the residual gas.

We studied the correlation between the transitional regime and the presence of impurities. In figure 2 it is shown a typical transitional regime of the thruster and a discharge evolution with different re-start-up processes. We observe a significant increase of the impurities once the thruster is first started, specially the N_2 trace. There seems to be also a reasonable correlation between the water trace and the discharge current, but with a certain delay. On the other hand, the re-start-up process recovers the history of the evolution. This means that the thruster shutdown period is just a gap in the time evolution. Moreover, if the thruster is re-started when the stationary current is achieved, no transitional regime is observed.

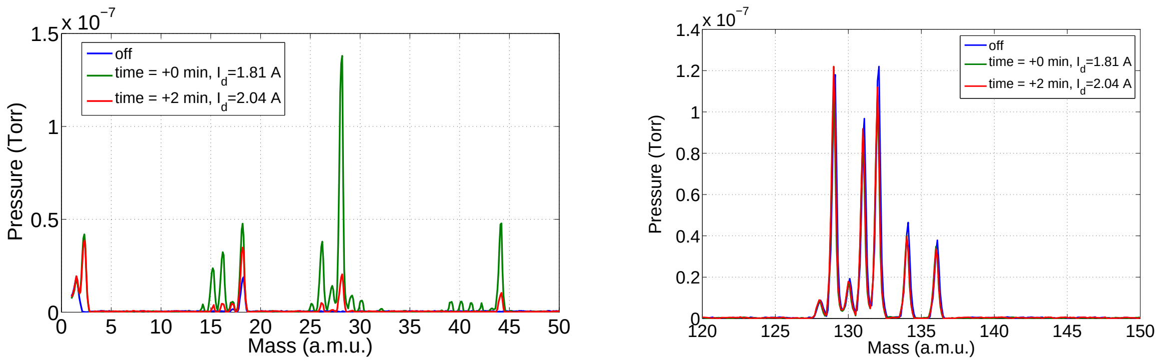
Figure 3 shows the typical mass spectrum of the residual gases in the start-up process. After two minutes the release of impurities decrease significantlly, with the exception of water and Hydrogen. Figure 3b points out that Xenon is unaltered during the transitional regime. Are the impurities air? It doesn't seem since the level of Nitrogen, Oxygen, and CO_2, are not in the correct proportions. It could be water plus the products of the oxidation and sputtering of BN.

We observed along several experiments that the exposure of the thruster to the atmospheric environment is a key factor in the appearence of the transitional regime. This exposure is directly related to the presence of impurities in the residual gas of the thruster. And the transitional regime is always related to the presence of impurities. So if the thruster is purged of those impurities, there is no evidence of the transitional regime. However the magnitude and duration of the transitional regime is not only determined by the amount of



(a) (b)

Figure 2. Transitional regime of experiment 1. Discharge current with different residual gas traces. $I_d(\infty) = 1.68(A)$, $p_{ref} = 10^{-8} torr$. **(a) Typical behavior of the transitional regime. (b) Transitional regime with re-start up processes. The history is recovered.**



(a) (b)

Figure 3. Mass spectrum of the residual gas of the exhaust of the thruster. (a) The main gas traces during the start of the thruster. (b) Xenon spectrum at the ignition.

impurities. Table 2 shows the characteristic values of the I_d-peak for different experiments. The magnitude of the peak, in terms of the increment in the discharge current, is ΔI_d, and Δt is its time period. Experiments 1 and 2 were performed at the same conditions, but different exposures to the atmosphere, whereas experiment 3 was performed with a segmented electrode thruster with carbon velvet electrodes.[5,8] The carbon velvet is a low SEE, low sputtering and low back flux material. Apparently, the velvet texture could probably retain air and water products after the air exposure. However, in the experiment 3, the amount of impurities present in the residual gas of the thruster was similar to the experiment 1, but the transitional regime was of lower magnitude. This observation indicates that the physical mechanism behind the transitional regime is more complex than the outgassing process of impurities.

B. Location of the gas impurities

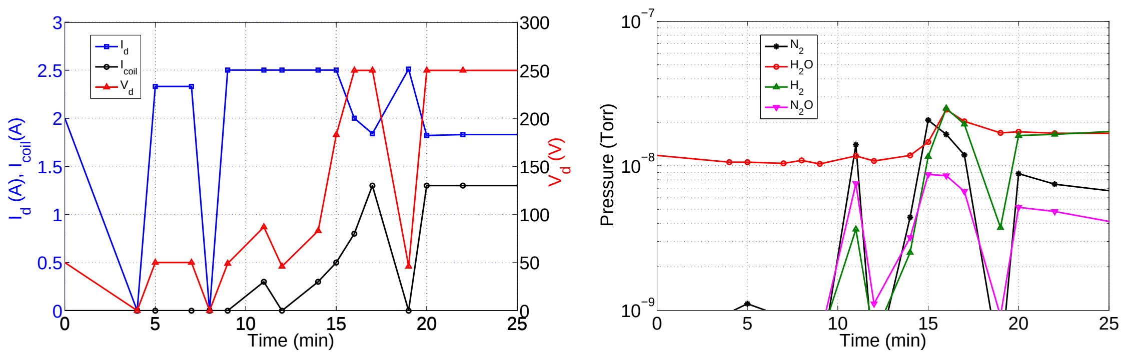
We studied the location of the gas impurities considering as suspects the different elements of the facility, namely, the cathode, the anode, the magnetic circuit, the vacuum chamber, and the walls of the thruster.

To determine the possible location of the impurities inside the cathode, we performed cleaning cycles before the ignition of the thruster. These consist of the injection of Xenon and the use of the heater several times. Results revealed no traces of impurities in the mass spectrum of the gas. Similarly, a pre-heating process was made for the magnetic circuit before the ignition of the thruster. Several energization cycles of the magnetic coils were performed to heat any gas present in the magnetic coils cavity, and higher pressures of gas impurities were not found.

	Exp. 1	Exp. 2	Exp. 3
$\Delta I_d(A)$	0.65(38.9%)	0.44(22.8%)	0.14(7.18%)
$\Delta t(min)$	19	31	20
$p_{N_2}(ntorr)$	134	582	196
$p_{H_2O}(ntorr)$	44	123	89
$p_{H_2}(ntorr)$	31	1	60
$p_{N_2O}(ntorr)$	47	182	55

Table 2. Peak values of the transitional regime.

In the case of the anode, we made a different experiment. The anode is a metallic plate which can be *coated* by a layer of dielectric material.[9] In order to heat the anode surface, but not the walls of the thruster, we turned-off the magnetic field during the plasma discharge, thus becoming a simple glow discharge. Figure 4a shows the changes of the discharge current over the time and the variation of the discharge voltage in the experiment. Figure 4b shows the measured residual gas traces. We can conclude that, first, the anode is not the source of the impurities since the operation without magnetic field do not produce an increment in the residual gas traces, and second, the magnetic field has an important effect in the transitional regime, because the impurity level increases as soon as the magnetic field increases and the discharge operation switches to the typical Hall thruster operation with the ionization and acceleration inside the channel.



(a) (b)

Figure 4. Anode experiment. The magnetic field is gradually increased during the plasma discharge. (a) The current-voltage curve of the experiment. I_{coil} is the current of the magnetic coils. (b) The pressure traces of the impurities.

We also studied the possibility that the vacuum chamber was the source of the impurities.[10] We did an experiment which consisted of injecting nitrogen and air directly into the vacuum chamber from a valve located behind the thruster. Previously the thruster was purged of impurities. The injected gas flow was progressively increased from 0 to about 11 sccm. Without the thruster and cathode gas flows, the background pressure was $6.4 \cdot 10^{-7}$ torr when the additional gas flow rate was increased to about 11 sccm. Results showed that there was no evidence of the transitional regime in the discharge current. Thus even with an increased level of impurities inside the chamber, the thruster operated in normal regime. Therefore, it is suggested that first, the vacuum chamber is not the source of the impurities, and second, the physical mechanism of the transitional regime depends on the location where the impurities come.

A possible source of impurities could be the thruster channel walls. This suggested is based on the fact that Boron Nitride grade HP used as the thruster channel wall material has a high porosity (about 15%) and a high capacity to be hidrated and de-hidrated. Moreover, since carbon velvet also has an effective high surface area, but it does not produce transitional regime or at least much weaker, it seems that Boron Nitride could be chemicially sensitive to the impurities.

III. Discussion

Shall now consider possible physical mechanisms, which could be potential responsible for the presence of impurities in the channel walls and their outgasing during the thruster startup. When the thruster is in contact with the atmosphere, the BN captures water, N_2, and other gases. Then, by plasma heating, the surface of the walls release the water and other impurities in a diffussive-like process. Thus the time period of the transitional regime is possibly governed by the difusion time of the impurities from the walls. But, how the impurities affect the discharge current?. There are a number of possibilities: (i) higher current due to the ionization of the impurities, (ii) higher conductivity due to an increase of the electron-neutral collisions, (iii) the modification of the plasma-wall interaction, and (iv) higher electron current due to instabilities of the plasma discharge, or due to higher plasma turbulence.

The first two hypothesis are related to the collisional processes induced by the gas impurities. Both ion and electron currents could be increased by ionization, whereas electron current could also be increased due to more electron-neutral collisions with impurities. These collisional processes could be relevant if the atom density of the impurities near the wall, n_{imp}, is high enough. Let's estimate the value of n_{imp}. Assuming that the total pressure of the impurities is $p_{imp} \sim 0.1\mu torr$ near the walls, and the temperature of the impurities is $T_{imp} \sim T_{wall} \sim 1000K$, with T_{wall} the wall temperature, the atom density of the impurities is,

$$n_{imp} = \frac{p_{imp}}{\kappa_B T_{imp}} \sim 10^{15} m^{-3}, \tag{2}$$

where κ_B is the Boltzmann constant. On the other hand, the near-wall Xenon density, n_{Xe}, assuming the total recombination of ions at walls, is

$$n_{Xe} \sim n_e \sqrt{\frac{T_e}{T_{wall}}} \sim 10^{18} m^{-3}, \tag{3}$$

for typical values of the plasma density, n_e, and the electron temperature, T_e, within the thruster. Therefore it seems that apparently any contribution to the collisional processes by the impurities is marginal compared with those related to Xenon.

We measured the ion current at the plume of the thruster to find out whether ion or electron currents were affected by the transitional regime. Figure 5 shows the results of the experiment 1. Interestingly, the increment on the discharge current, $\Delta I_d \simeq 0.4 I_d(\infty) \simeq 0.65$ A, is distributed similarly on the ion ($\Delta I_i \simeq 0.31$ A) and on the electron currents ($\Delta I_e \simeq 0.34$ A). The maximum ion and electron currents are 24% and 88% higher than the stationary values, respectively.

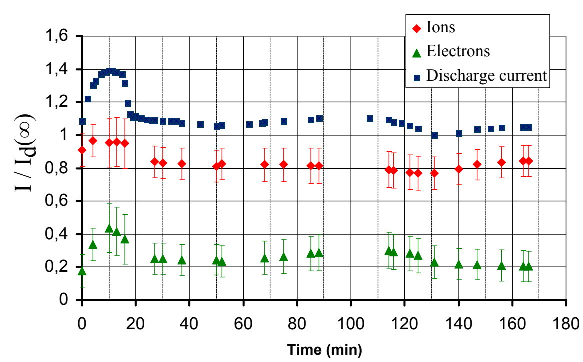


Figure 5. Plume measurements of the ion current in experiment 1.

We did another experiment to study the collisional processes induced by the gas impurities. Once the thruster was previously purged of impurities we injected progressively a gas mixture of Xenon and N_2 through the anode (in another experiment we injected a gas mixture of Xenon and air obtaining very similar results). Figure 6 shows the plume measurements of the ion current and the main oscillations of the discharge current during the experiment. We can see that the injected N_2 was ionized and produced more ion current, whereas the electron current was almost the same all the time. In particular, the injection of 10.65 sccm of N_2 produced an increment of $\Delta I_i \simeq 0.3$ A on the ion current, which represents a ionization efficiency of 40%

with respect to the N_2 gas flow. This implies that gas impurities do not produce more conductivity on the electrons, and second, the increase of the discharge current during the transitional regime can not be explained in terms of a larger mass flow of working gas. Apparently, the collisional processes related to impurities are not the main cause responsible of the transitional regime.

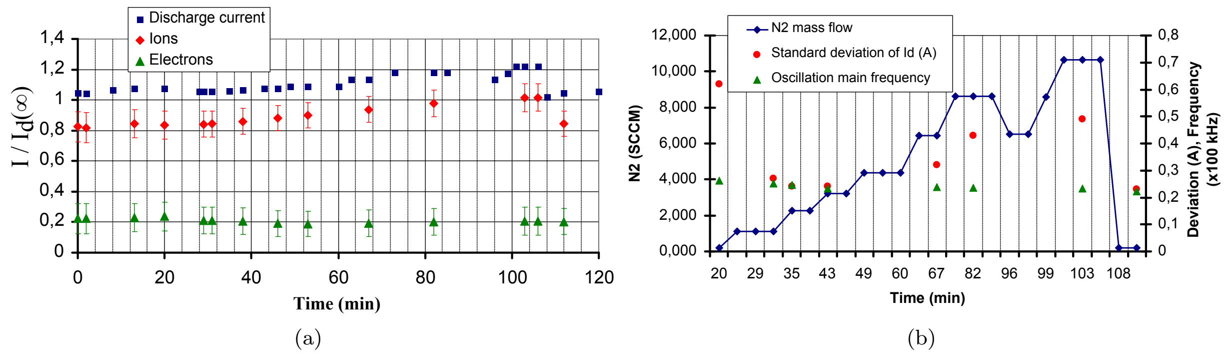


Figure 6. Injection of N_2 from the anode. (a) Plume measurements of the ion current. (b) Main oscillations of the discharge current.

Hargus and Pote[1] pointed out that plasma-wall interaction could be important in the transitional regime. They speculate that the secondary electron yield of the acceleration channel walls could be modified by hydration, or alternatively, by the de-hydration of the wall in the first minutes of operation following exposure of atmospheric conditions. And the modification of the secondary electron yield would affect near wall conductivity through the radial magnetic field. In addition, Ivanov et al.[11] pointed out that the recombination and ionization processes (for Xenon and impurities) near the wall could also enhance the near wall conductivity.

Experimental results[12] support the idea that the hydration of certain ceramic materials can produce an increase of the secondary electron emission. This could explain the fact that the segmented electrode thruster, with lower secondary electron emission from a section of the walls, has a transitional regime of lower magnitude. However, in abscense of more data, it remains uncertain if the increment on the near wall conductivity is high enough to explain the discharge current behavior during the transitional regime. It could also be possible that the presence of impurities outgassing from the BN walls of the thruster modified the Debye sheaths of the thruster, since they are very sensitive to local changes of the wall properties. Unfortunately, these questions are currently being studied with numerical experiments and is not possible to extract conclusions.

Finally, regarding to the plasma instabilities during the transitional regime, we can not conclude its relevance since more experiments are needed. Apparently the amplitude of the discharge current oscillations increases during the transitional regime but the main frequency remains almost unaltered.

IV. Conclusions

In this work we present a preliminary study of the transitional regime in the start-up process of a conventional Hall thruster. The transitional regime is defined by an increase in the discharge current and is present in a wide range of conditions, such as different operational parameters of the thruster, different magnetic field, and different materials of the walls.

The higher discharge current observed during the transitional regime is related to the presence of gas impurities (water, H_2, N_2...) coming from the ceramic walls of the thruster. These impurities appear when the thruster is exposed to the atmosphere. Different physical mechanisms have been proposed as responsibles of the transitional regime. Since collisions related to the impurities seem to be unimportant, the modification of the plasma-wall interaction is the most likely hypothesis. This conclusion is based on experimental results that indicate a modification of the secondary electron emission yield by the presence of absorbed water for different ceramic materials.

The transitional regime is not only important for laboratory experiments but also for space missions with a rapid deployment of the thruster after the launch. It should be taken into account in certain missions where the accurate knowledgement of the performance of the thruster in the first minutes of operation is of great interest, such as in close formations of satellites.

Future work should focus on the understanding of the physical mechanisms behind the transitional regime. First, experiments to determine the modification of the secondary electron emission yield by the presence of impurities at walls must be conducted. Second, plasma instabilities during the transitional regime must be studied. And third, efficiencies of the thruster during the transitional regime should be measured.

Acknowledgments

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