XENON GAS INJECTION IN SPT THRUSTERS

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Abstract

The present development of 2D hybrid code simulation of Closed Electron Drift (Hall) Thrusters (CEDT) makes possible a better defined comparison between experimental characterizations and code predictions. Various inputs are required in order to represent in a realistic way the physical conditions used in simulation codes. The present paper is focused on the work developed at GREMI in order to obtain a confident definition of xenon injection in the channel of a Stationary Plasma Thruster (SPT) and to examine the impact of various injection schemes on the thruster itself. This task has been achieved in three main steps. The first one was to develop simulations of gas injection structures, the second one was to obtain experimental data on gas distribution in the channel, the last one was to characterize the impact of the injector structure on the thruster characteristics.

The simulation codes have been developed on the base of particle in cell (PIC) approach, with non trivial assumptions on initial velocity distributions of gas beamlets leaving the injector holes. The atom-walls conditions have been represented in the two extreme cases of specular and perfectly diffusive ones.

An electron gun able to deliver a focused beam (10 keV, 2 mm, 10µA) has been developed in order to measure a local density distribution across and along the SPT channel, by using the local gas fluorescence signal recorded through a focusing lens and fibre optic system. The calibration of light emission as function of neutral density was done by using stationary xenon pressure conditions. A 2D translation unit is used to scan the thruster channel cross section (r,z) and the derived neutral density distributions are compared to code predictions for various injector structures.

Finally the impact of various neutral gas injection structures on thruster SPT100ML is presented and discussed. For similar operating parameters (gas flow, magnetic field, thruster voltage) data show that the tested gas injection system have not a strong impact on overall performance (thrust, Isp, efficiency) but they suggest the thruster plume is significantly modified.

Introduction

SPT devices have been studied for several years and their design is mainly resulting from pragmatic developments based on physical understanding. Facing the fast increasing interest of the CEDT's systems a better basic knowledge of the discharge and the plasma dynamics is required. In the frame of the cooperative research program GDR n°2232 (CNES, SNECMA, ONERA) several academic research teams are involved for experimental (Aérothermique Orleans, LPGP Orsay, GREMI Orleans) and modelling studies (CPAT Toulouse, CPHT Palaiseau) /1,2,3/

In spite of such long term efforts, simulations able to give confident results on lifetime and up-scaling are not presently available due to the complexity of the physical processes in particular electron transport.

The anode of a stationary plasma thruster which is located in the bottom of an annular channel also plays the role of the gas (xenon) distributor. Holes are shared out azimuthally on a grid to enable an homogeneous gas distribution. Their position is optimised according to two criteria : providing the most homogeneous distribution and minimising the influence of the discharge.

Previous numerical simulations and experimental (optical) investigations have shown that the dynamics of the ionisation zone is linked to the gas distribution in the channel. The successive filling-depletion of neutrals in the channel leads to low frequency axial movements and spread of the ionisation zone /9/. Results of the numerical studies also showed that the gas ionisation takes places preferentially in the centre of the channel /4/.

These physical processes influence the angular distribution of the ejected ions, an important parameter in the processes of the channel ceramic sputtering /5/ and interactions with the solar panels of the satellite /12/. Due

to the complexity of physical processes in SPT it is difficult to develop completely predictive simulation codes from the point of view of lifetime and up-scaling effects.
The aim of this research is to investigate the impact of several types of gas distribution on the ionisation and their influence on the plume divergence.
A description of the injection configurations and results of the related numerical simulations of neutral gas dynamics - without discharge - are presented in the first and the second part.
A diagnostic based on electron induced fluorescence has been developed in order to obtain in-situ measurements of local neutral density and test of simulation data. Description of the diagnostic and experimental results will be presented in the third part.
Time averaged optical diagnostics have been used to make pictures of the plume. The analysis of these results and discussion about their relation with the gas distribution are reported in the fourth part.

-Part I- Injection Configurations

In SPTs xenon is injected through a set of holes distributed azimuthally on the anode. This annular anode is located at the bottom of the discharge channel.

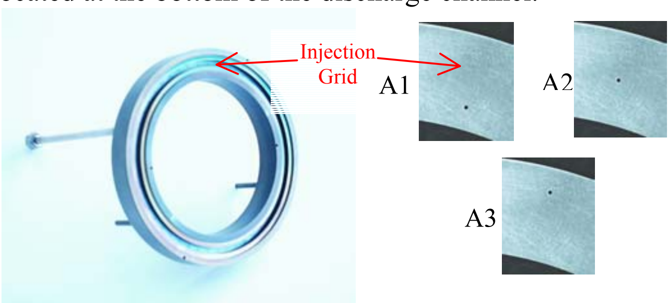


Figure 1 : Home designed anode and tested injection grids configurations

An anode structure has been designed at GREMI in order to make easy a modification of injection holes distribution. Three types of gas distributors are shown on the figure 1. Their difference lies in the radial position of the holes on the grid which is in contact with the plasma. The following configurations were tested: A1: holes on the anode inner radius, A2 : holes centred on the mean channel radius and A3 : holes on the anode outer radius (figure 1).

A previous study was accomplished in order to test the viability of such an anode : absence of significant impact on general thruster behaviour has been demonstrated.

-Part II- Simulations

The numerical model used here to simulate neutral dynamics is a part of the two dimensional PIC code developed at CPAT /10/. The description of this 2D PIC code and results are presented in several papers (for example /6/).
The neutral dynamics in the channel of the SPT100 laboratory model (ML) was simulated without discharge. The density distributions for the three configurations of injector (A1, A2, A3) are shown below (figure 2 to 4).

-II-1- Influence of boundary and initial conditions

Various inputs in simulation codes are required to represent the physical conditions in a realistic way. Among them, we decided to study the influence of initial conditions of velocity distribution of gas beamlets leaving the distributor. Boundary conditions concerning interactions with walls (two extreme cases : specular and diffusive types) were also studied.

Interactions with walls – For a given injection type in the case of specular interactions with walls (see figure 2a) the density is quite constant along and across the channel excepted near the distributor. But for the case of diffusive interactions with walls (figure 2b) radial and axial density gradients are higher. The density lines are curved towards the anode, a density minimum is in the center of the channel and with increase near the walls.
In the contrary for the specular case the maximum of density is in the middle of the channel.

Initial velocity distribution : Gas is injected with axial velocity component depending on the beamlet expansion. According to considerations about the expansion of a fluid in the vacuum - state at the exit of those holes – the jet is conical with an expansion angle included between 60° and 90°. Those two conditions were tested (figure 2b and 2c).

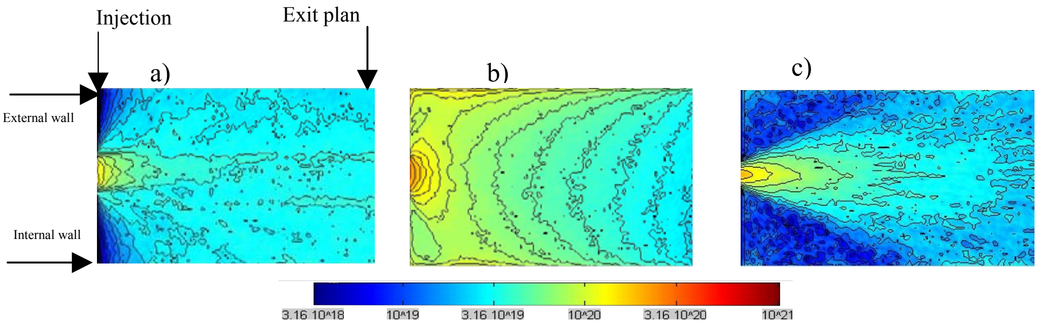


Figure 2 : Influence of initial and boundary conditions on the gas distribution. Mass flow rate of 5mg/s, T=800K. a) specular 90° ; b) diffusive 90° c) diffusive 60°.

Investigations on the influence of temperature and mass flow rate have also been performed but they don't show any qualitative differences whatever initial jet expansion or wall reflection conditions.

-II-3- Comparison of injectors

Here are presented results of simulations for the most disadvantageous conditions (injection into 90° angle cone, diffusive neutral-wall interactions) , showing close density distributions among the three holes positions (figures 3 and 4).

Note : differences between density lines topography should be accentuated for a smaller injection angle or a wall reflection condition between totally specular and totally diffusive one.

Results of simulations show that the gas distribution in the channel is dependant on the injection mode.

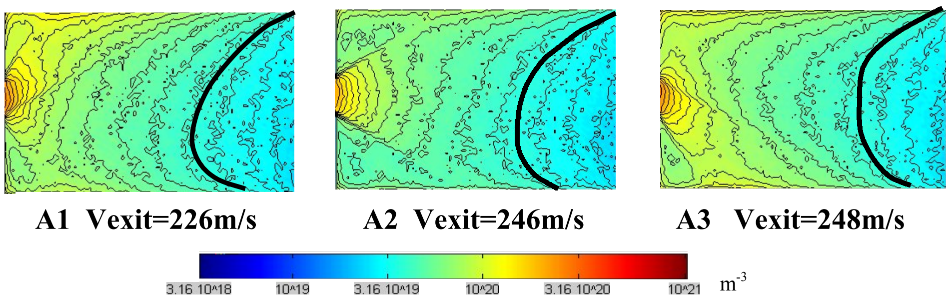


Figure 3 : Influence of holes position (mass flow rate : 5mg/s, T=800K, diffusive reflections with walls)

For every case the lines are parabolic with high axial gradients, and density increases close to the external wall (figure 3 and 4).

If the injection holes on the grid are centred (A2) or near the external wall (A3), the lines become flat and the mean velocity increases. The axial gradient is softer in these cases. Gas distribution is more homogeneous in the exit zone.

A1 simulation shows higher axial gradients near the

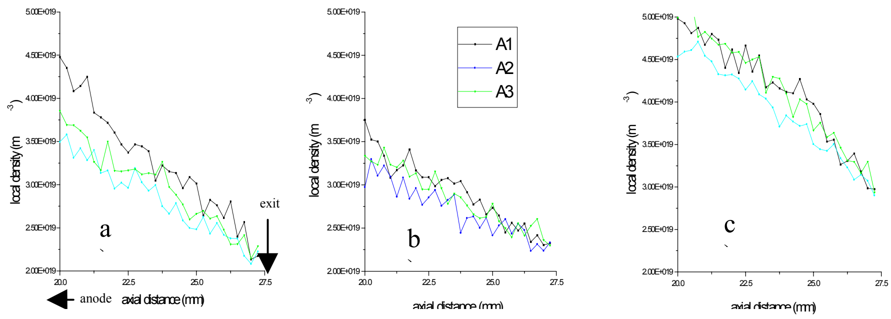


Figure 4 : Neutral density axial evolution in the near exit zone of the channel (mass flow rate : 5mg/s, T=800K, diffusive neutral wall interaction : a) near the internal ceramic, b) in the channel mean radius, c) near the external ceramic.

internal ceramic in the exit zone. In the centre of the channel, density gradient is not so pronounced and the most dense areas are located near the walls inducing a high local radial gradient. Ejection velocity is the lowest of the three cases.
For every case there is a more or less high radial gradient of density and this effect seems stronger near the anode.

Because those results lie on uncertain simulation conditions the development of a space resolved diagnostic able to measure neutral density appears necessary.

- Part III- Density measurements

-III-1- E.I.F Method

The Electron Induced Fluorescence (E.I.F.) presented here is an original optical method developed at GREMI to measure local atomic Xenon concentration in the pressure range met in a SPT channel.
This technique lies on the principle of excitation – de-excitation of an atomic particle considered at rest and submitted to the action of a homogeneous electron beam.
Let's consider a system of particles in a stationary state interacting with a quasi one dimensional electron beam. Along the beam the electrons – atoms collisions transfer the system to an excited state with light emission consequent to relaxation with the probability P_k :

$$P_k = n_e.v_e.\sigma_k = \Phi e.\sigma_k = \frac{I_e}{q.S_{beam}}.\sigma_k$$

Where n_e=electronic density, v_e=electron velocity, σ_k=excitation cross section and S_{beam}=electron beam section.
With this non intrusive and calibrated characterization technique the atomic Xenon topography with a spatial resolution of less than 3 mm^3 can be obtained. The measurement volume is defined by the intersection of the excitation beam and the optical focusing point (figure 5 right).
The radiative lifetime of the upper states being extremely weak (a few 10^{-8} s), the de-excitation happens quasi instantaneously. Moreover the particles mean velocity is of the order of hundreds m/s /7/ so that the corresponding atoms movement before the photon emission is of the order of the µm. Then this measurement can be considered as local one.

-III-2- Experimental set-up

Tests conditions - The vacuum chamber and diagnostics used for E.I.F. are shown on figure 5. A SPT-100 channel replica has been designed to perform in-situ measurements. It was built in aluminum because an equipotential area between the gun and the channel is needed in order to better confine the electrons, to

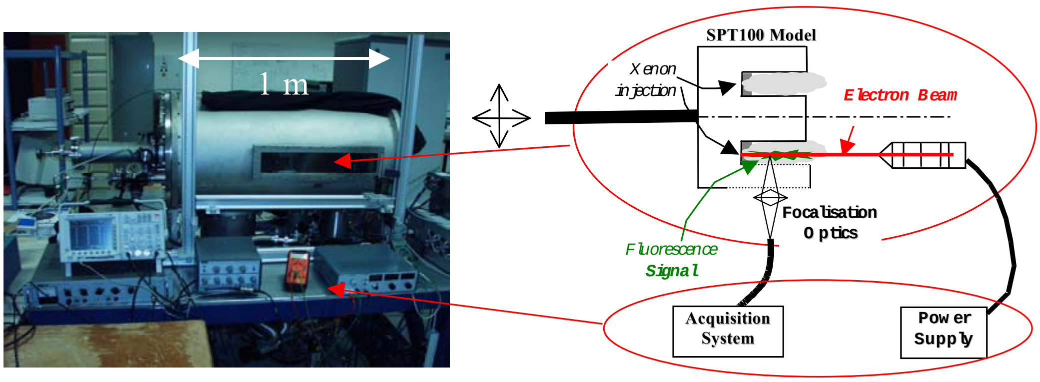


Figure 5 : Test structure with the cylindrical vacuum chamber in the background (0.5m diameter) and electrical and optical diagnostics (from left to right : oscilloscope, photo-multiplier, low frequency generator, electron gun control).

conserve their energy and to avoid the beam dispersion. The replica was equipped with the SPT-100 home designed anode and A2 injection configuration to perform in-situ measurements.

The replica is equipped with a quartz window along the z-axis and is maintained into the vacuum chamber by the mean of a two dimensional (r,z) moving axis which enables to scan an r-z plan perpendicular to the window (figure 5).

Electron beam characteristics – The electron beam is created by an electron gun composed of an emissive cathode and focusing and accelerating grids. The beam diameter (1.5mm) and the electronic energy (7-10 keV) depend on the last grid accelerating potential (7-10 kV) but remain constant along the beam (10 centimeters).

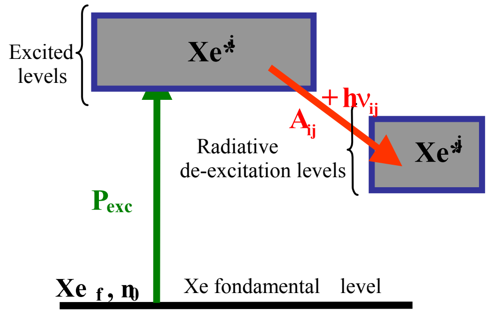


Figure 6 : EIF scheme

Calibration – The measurements were firstly managed without spectral filtering and a photo multiplier detected all the photons emitted in the range 400-900nm as showed on figure 6.
Figure 7 shows that the curves corresponding to the emission signal (normalized by the electron beam current) for calibration of the diagnostic are linear in the range 10^{-3} – 10^{-4} mbar. The signal level (S) corresponds to the integration of light emission between 400 and 900 nm. It can be expressed as a linear function of the local neutral gas density for a constant electron beam current thus :

$$S = K\, n_0\, I_e$$

Where K is a function of excitation cross sections depending on electron energy or average probability for light emission.

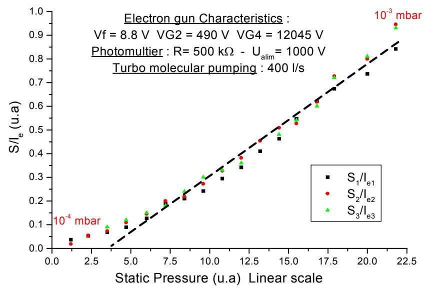


Figure 7 : Calibration curves at static pressure.

Moreover the turbo pumping was limiting the maximum pressure. For SPT-100 at 5mg/s the neutral density in the channel is expected varying between 10^{-3} – 10^{-4} mbar. A deviation of the linear increase shown by this experiment is not expected in the range of SPT neutral densities. Experimental tests will be achieved for a reduced mass flow of 1mg/s which is well in this calibration range.

-III-3- Density profiles

The aim of this measurements is to validate the simulation assumptions about initial and boundary conditions.
A significant level of light resulting from the electron beam impact on anode structure was observed. In order to record E.I.F. photons emitted by Xenon, a spectrometer was used to selectively record E.I.F. emissions at 823.2 and 828.0 nm. Figure 8a gives radial evolution 2mm after the distributor exit for the three numerical simulation conditions studied in part II-2.
Figure 8b shows results of local measurements carried out in the same axial position.

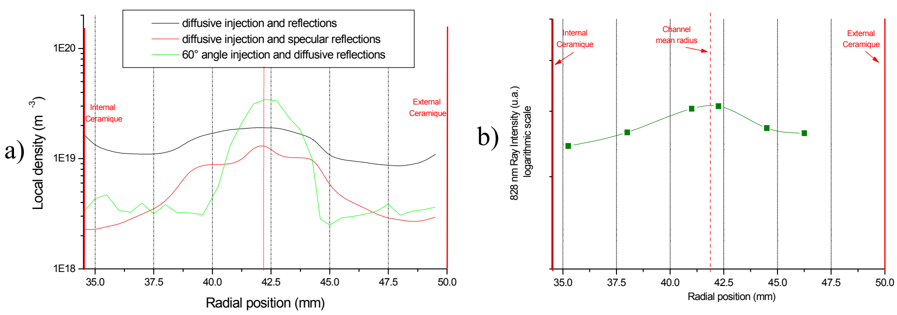


Figure 8 : a) Numerical simulations and b) Local density measurements at reduced mass flow.

Those preliminary data show that the initial condition about the jet expansion is nearer of a 90° angle and the neutral-wall interactions seem more diffusive than specular. This work is in progress.

-Part IV- Impacts of gas injection on thruster behavior

One of the points developed in previous studies was to obtain a detailed view on transient phenomena occurring during the spontaneous fluctuations of SPT discharge. The most important results obtained by looking at the oscillation regime of thrusters (reported in several papers) are : i) a rather small instantaneous energy spread of the ejected ions with time varying mean energy, ii) a spatial fluctuation of ionisation/acceleration zone, iii) a time varying divergence of the plume.
Tests were performed with the standard thruster and the home made anode in the PIVOINE facility described in /8/ and general performances of the thruster were not affected by the injector type.
The aim of this part is to present data obtained with time averaged diagnostics giving information on the averaged behaviour of the thruster for the nominal point (300V, 5mg/s).

-IV-1- Time averaged images of the plume

Imagery is a non intrusive method which enables access to the areas where it is difficult or perturbing to use probe diagnostics. A CCD camera was used to provide average pictures of the plume with time exposure of a few milliseconds and a good spatial resolution (0.3mm/pixel).
The camera line of sight was perpendicular to the thruster axis. Interferential filters centered on 825 and 525 nm were used in order to discriminate the atomic and ionic lines (823.2nm and 529.2nm respectively). Their spectral bandwidth measured by using a tungsten lamp source is 20 nm. This is low enough to obtain selective information on ionic and neutral emissions /9/.

Abel transforms have been applied to the half of the picture opposed to the cathode location and enable the estimation of the plume divergence by several means :

- by looking at the radial profile of light emission for neutrals and ions (figures 9).
- By analyzing the ionic emission evolution on the thruster axis (figure 10).

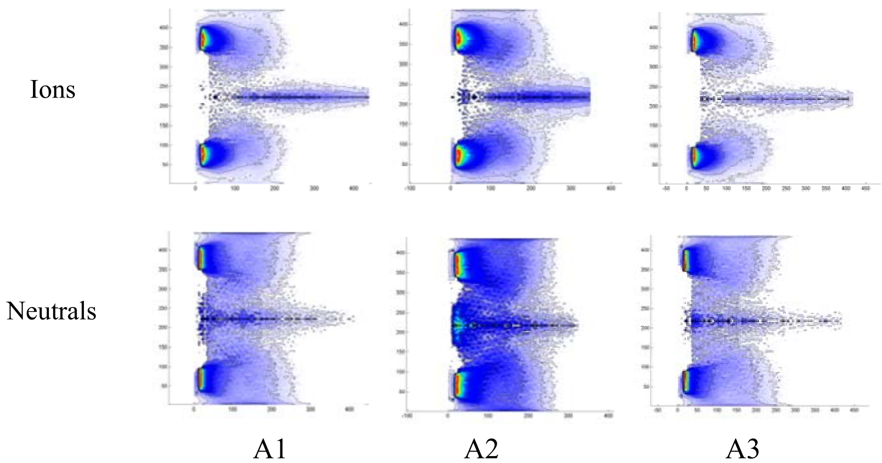


Figure 9 : Abel transforms performed on ionic and atomic filtered pictures for the three injection configurations.

For the second point it was shown that current density comes from all around the channel and make this area singular from the point of view of light emission /11/. So the plume is more divergent when the light intensity is concentrated near the thruster exit. Thus information on the jet expansion with spectral resolution can be obtained.

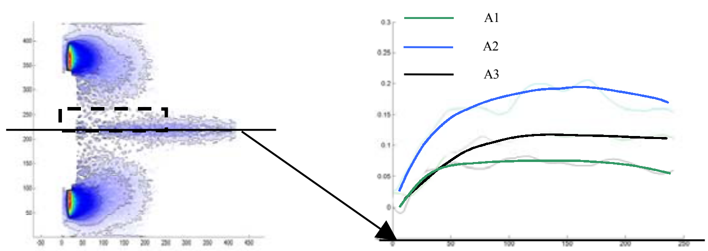


Figure 10 : Axial evolution of ionic light emission.

Those investigations show that :

- in terms of plume divergence A2 configuration leads to a more divergent plume than A3 injection.
- in terms of neutral emission near the channel exit, the pictures for the A1 and A3 configurations show less neutrals than for A2.

-IV-2- External Neutral Density

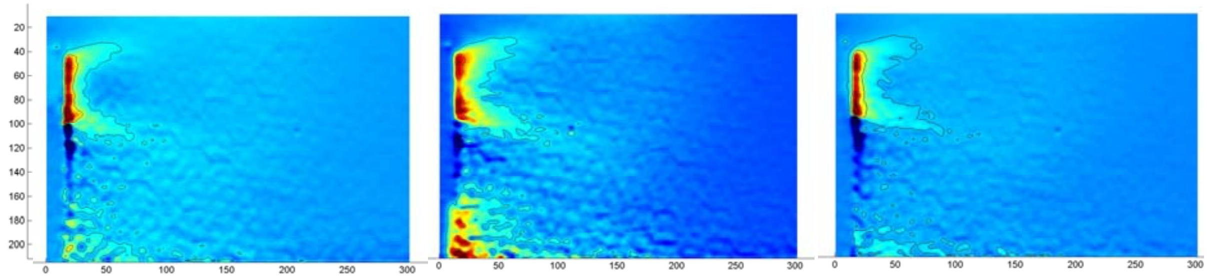
Assuming that the electronic temperature and the plume neutrality are roughly constant near the channel exit area neutral density can be calculated /9/.
The ionic and neutral emissions are defined by:

$$I_{neutral} = n_0 n_e \langle \sigma v_e (T_e) \qquad I_{ion} = n_i n_e \langle \sigma v_e (T_e)$$

If we assume a relative constant electron energy in the plume the density is roughly estimated as :

$$n_0 \propto \frac{I_{neutral}}{\sqrt{I_{ion}}}$$

Results of such an approximation are reported on figure 11. Differences on the neutral composition of the plume according to the injection mode can be observed but for each case two areas with high density are localized next to the internal and external walls of the discharge channel. The orientation of these areas depends on the injection type and the differences are more sensitive in the middle of the channel.
Near the channel exit the assumption of a constant electronic temperature is certainly not valid anymore but the observed phenomena is also met in the numerical simulations of the discharge /4/.



A1 A2 A3

Figure 11 : Calculated neutral density.

The observed neutral population have two origins : injected neutrals being not ionized (300 m/s) or neutrals resulting of ions recombination with walls. In this last case their velocity is expected to be much higher than the injected neutrals. The decrease of the neutral emission intensity has been recorded in the ultra fast switch experiments but these data can not give an immediate answer to this question.

Conclusion

The impact of the neutral gas (Xe) feeding at the bottom of the channel of SPT thrusters was investigated by using a versatile design of the annular anode. Simulations of neutrals for various injector shapes was achieved by using PIC codes. These codes show that results are sensitive to injection type and neutral-wall interaction assumptions. It was clear that an experimental basis would be useful to study the conditions of gas injection. This experimental determination was developed by using the electron impact fluorescence with a high energy, small diameter electron beam . Preliminary results show that this approach is a successful one and suggests that 45° half-angle for the injected beamlets and diffusive interaction with walls is appropriate.
The impact of various types of injectors on the SPT-100ML performances has been investigated. For rough characteristics, such as I(V) characteristics or thrust, the impact of the beamlets injector type evidenced not significant differences. Nevertheless the plume divergence, derived from optical diagnostics, appear to be more sensitive to the injector design. This work is in progress both for the experimental validation of injection simulations and for connection with the 2D hybrid code of Hall thrusters developed at Toulouse University.

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