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OVERVIEW OF RECENT RESEARCH ACTIVITIES ON HALL EFFECT THRUSTERS PERFORMED AT THE LABORATOIRE D'AÉROTHERMIQUE

A large research programme on Hall thrusters has been initiated in France in 1996. This programme includes modelling, as well as theoretical and experimental approaches. These researches are coordinated in the frame of a national Research Group. Recent results obtained at the laboratoire d'Aérothermique taking part to the activities of this group are presented. These results describe to ion and electron properties in the plasma flow in the surroundings of the thruster channel exhaust.

hall thrusters, ion and electron properties, hollow cathode, diode regime, electric potential, plasma discharge, frequency, density

Introduction

Numerous geostationary satellites for telecommunication are now equipped with electric thrusters because of their advantages in terms of gain in platform mass. Furthermore, it appears that interplanetary missions could use electric propulsion to allow reasonable mission duration. In the field of electric propulsion, Hall Effect Thrusters (HET), also named Stationary Plasma Thrusters, are nowadays considered as the most promising device for missions like satellite station keeping on geostationary orbit, orbit transfer and space probe trajectory control for interplanetary exploration due to their high level of performances (especially for specific impulse). Moreover, such a kind of electric thrusters can operated in high specific impulse regime as well as in high thrust regime. This dual mode is considered as a real advantage for near future missions.

A short overview of the research activities with some examples of recent experimental results obtained at the laboratoire d'Aérothermique of CNRS at Orléans (France) in the field of Hall propulsion will be given. Essentially, the results will concern ionic properties, thermal evolution of the sub-elements of the thrusters, which is correlated to the ionic fluxes, and the electron properties near the exhaust of the external hollow cathode.

1. Hall Effect Thruster

The basic principle of functioning of a Hall Effect Thruster (HET) has been previously described in many papers. Schematically, a partially magnetized discharge is sustained in an annular channel formed by two walls made of ceramics. This discharge needs an external electron flux produced by a hollow cathode and an atomic gas flow arriving from the rear of the channel. A magnetic field created by external coils traps the electrons to ensure a high enough electron time residence in the channel to favour non elastic collisions. These collisions give an essentially single ionized gas. Generally the working gas is xenon due to its mass, its absence of toxicity and its low first ionisation potential (12.13 eV). Then, the ions are accelerated to a high velocity (around of 20km/s) by the self consistent electric field appearing near the channel exhaust as the result of the drop in electron mobility. Contrary to ion thrusters, the electric field in HET is obtained far from the electrodes. The acceleration of the ion is related to the potential map which is generally close to the magnetic map. The magnetic topography plays an important role in the optimisation of the HET. One have to also note that the magnitude of the magnetic field near the channel exhaust is chosen in order to only magnetize the electrons (Larmor radius of a few mm).

The optimisation of HET needs a good understanding of the physical properties of the plasma discharge. With this goal which requires a large effort in experimental research and modelling, we present some results obtained at the laboratoire d'Aérothermique during the last year. They complete the previous and the current works.

2. Velocity of ions

A Fabry-Pérot (FP) interferometer has been recently used to determine the temperature of Xe atoms. (823.16 nm emission line). This measurement allows an estimation of the surface temperature of the ceramics and a comparison of the values obtained by optical emission of N_2^+ (first negative system observed after the injection of a small amount of N_2).

The FP bench can also be employed to measure Xe^+ ion velocity [1]. The light emitted by the plasma and by a reference plasma source (for the zero Doppler shift) are combined and then the beam enters in a plane Fabry-Pérot cavity with 3.4 mm between the two mirrors. This cavity is optimized for wavelengths from 450 nm to 550 nm. The free spectral range is equal to 44.1 GHz and the spectral resolution is about 0.75 GHz, giving an accuracy around 2.5 km/s for an axial velocity of 20 km/s.

The measurements have been performed with the SPT100-ML thrusters installed inside the PIVOINE facility. The line of sight of the FP diagnostic is oriented at 64° with respect to the thruster axis. The spatial resolution is 4.4mm and the depth of the observed plasma is around 30 cm. This weak spatial resolution which is induced by the integration along the line of sight is compensated by the easiness of its implement. FP interferometry is a complementary tool to the Laser Induced Fluorescence (LIF) diagnostic. The Fig.1 shows the ion axial velocity in comparison with previous measurements obtained by LIF. A good agreement is observed out of the channel with the same limit, around 20 km/s. Inside the channel the ion speed around 370 m/s can be correlated to the velocity of the neutral species before ionisation.

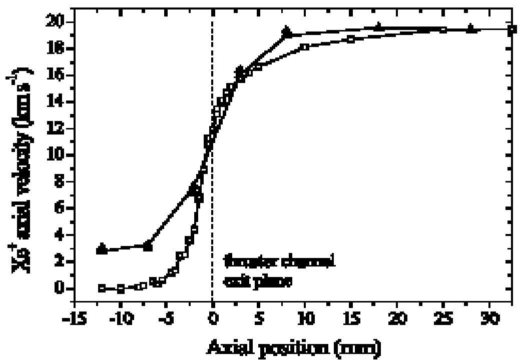

Fig. 1. Xe^+ ion axial velocity along the channel axis under standard thruster operating conditions. Fabry-Pérot data (triangle) and LIF data (square).

The local XeII velocity is linked to the local electric potential in the plasma discharge. The voltage profile obtained from the ion velocity (FP) is in good agreement with the LIF one.

The Fig. 2 presents the ion axial velocity as a function of the discharge voltage and the axial thrust measurements. These two quantities exhibit the same behaviour (in a first approximation the thrust is proportional to the discharge voltage if the efficiencies of ionization and energy gained are close to one.

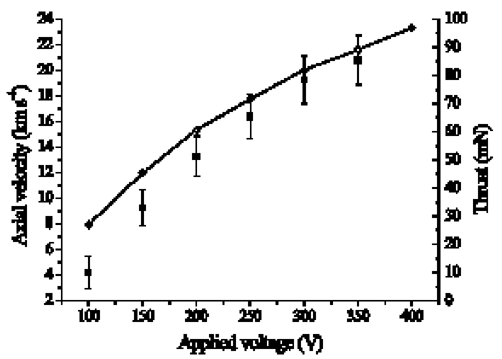

Fig. 2. Axial ion velocity and thrust as a function of the applied potential.

The FP measurements have been performed with Dr. D. Pagnon of the LPGP laboratory of the University of Paris-Sud.

3. IR thermography

Infrared thermography of HET allows to determine the absolute temperature of the external surface of the different sub-elements if the emissivity of the materials has been previously measured. The interest of this measure is evident from different points of view: First, it gives information about reached thermal levels of anode, coils, internal and external ceramics in a transient and in the stationary states. Second, it permits to follow the thermal behaviour of the thrusters in order to prevent damages due to thermal stress in ceramics, destroying of the isolation of wires of the coils, and appearing of hot spots on ceramics. Morever, this non intrusive diagnostic permits to test new HET (i.e. bi-stage) or HET operating in non usual conditions (i.e. high discharge voltage). The thermal behaviour of a PPS1350-G thruster manufactured by SNECMA has been monitored by means of an infrared camera (FLIR system) with a photodetector having 320 x 240 pixels operating in the 8 – 9 μm spectral range [3]. An image of the SPT100-ML thruster running under standard conditions (Vd = 300V, mass flow rate = 5 mg/s) is shown on Fig 3 with ε = 0,92 (measured at the CRMHT laboratory at Orléans).

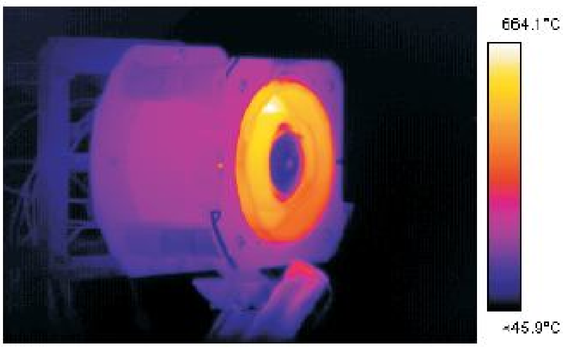

Fig. 3. Calibrated infrared image of SPT100-ML under standard operating conditions (1350W)

The Fig. 4 presents the thermal evolution recorded during about 3 hours after thrusters ignition under a power of 1350W. After an ignition time of the discharge in the order of 1 μs a quasi thermal steady state is obtained after around half an hour. This heating is mainly due to the energy of the ions striking the surface of the ceramics and additive heat is also coming from the dissipated energy in the coils. Radiative flux of energy and electron impacts seems to be negligible. It appears that the inner ceramic is always the most warm in reason of the shape of the magnetic lens. After 170 mn the discharge is stopped and the temperature rapidly decreases.

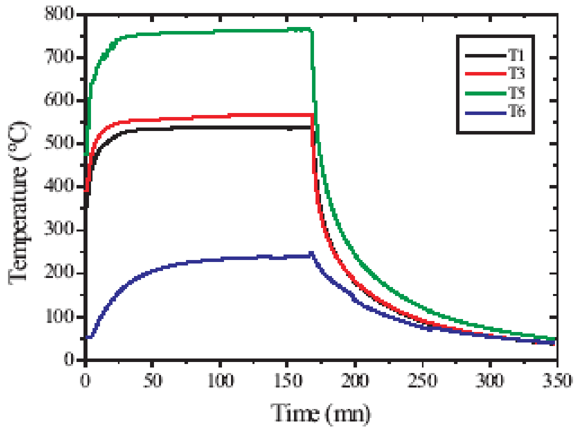

Fig. 4. Temperature of different SPT HET components as a function of time during a thermal cycle under standard operating conditions.

The IR thermography can also be used to evaluate the local value of the heat flux that is an important input parameter for thermal numerical code or to examine the effects of a change of operating conditions (i.e. effect of the map of magnetic field, mass flow rate, discharge voltage or material of the ceramics).

The infrared imaging has been carried out with Dr. P.Echegut (CRMHT laboratory at Orléans).

4. Hollow cathode in diode regime

The PPSX000-ML (laboratory model) operating with a high current discharge will be equipped with the cathode M-20 manufactured by the Kharkov Aerospace Institute (KhAI). This cathode has been tested in a diode regime at the GREMI laboratory in a low pressure chamber in the range 5 – 25 A. Its nominal mass flow rate is 0,4 mg/s of xenon.

The static and the dynamic behaviours of this heaterless hollow cathode have been studied. The “plume” mode and the “spot” mode have been observed (Fig. 5). The first one appears for high discharge voltage and low mass flow and the second one for large mass flow rate and low voltage. The “spot” mode produces the lower oscillations of the discharge voltage.

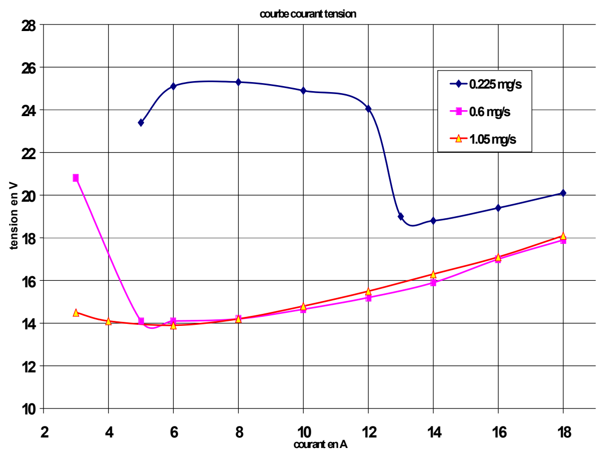

Fig. 5. Characteristic curve (I – V) for three xenon mass flow rates (0,22 and 0,6 and 0,8 mg/s)

5. Hall thruster dynamic – low frequency

The low frequency dynamic of the discharge of the SPT100-ML equipped with a “hot” hollow cathode manufactured by MIREA (Moscow) has been analysed by electrostatic probes.

The time average electron temperature (T_e), density (n_e) and plasma potential (V_p) have been determined from the characteristic curve of an electrostatic probe set near the exhaust plan of the thruster. T_e and n_e are increasing with the discharge current when V_p and T_e are decreasing with the mass flow.

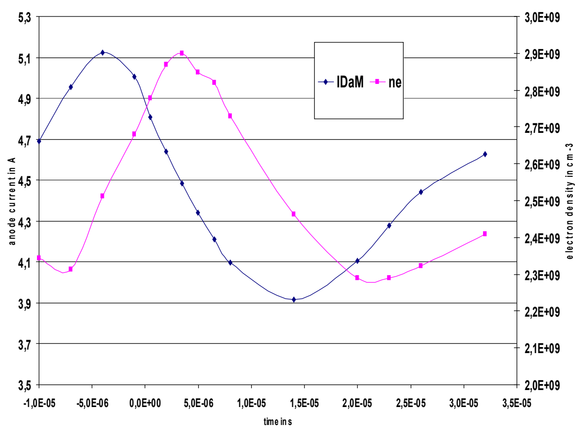

Fig. 6. Electron density in cm^{-3} and anode discharge current (in A) as a function of time.

The dynamic of the electron density (Fig. 6) has been observed by a time resolved analysis of the current collected by the probe using a trigger on the high part of the anode discharge current (IdA).

The 7,5 µs time delay between the maxima of n_e and IdA is correlated to the time of neutralization of the ejected ions by the electrons emitted by the cathode. With the same method, the time dependence of the plasma potential (Fig. 7) permits to verify the usual correlation between n_e and V_p (same time delay of 7,5 µs).

The electron temperature is quite constant as a function of time with a value around 6,5 eV.

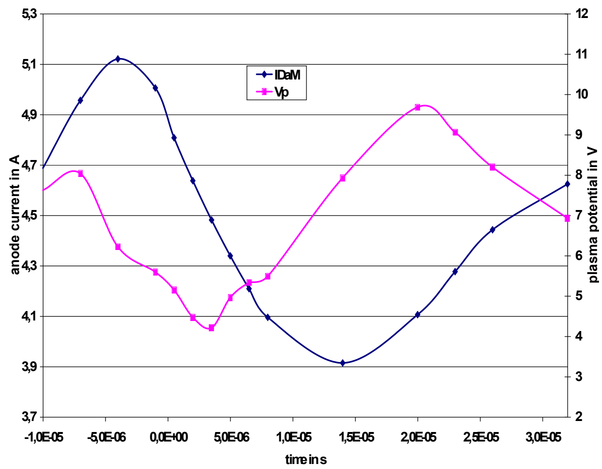

Fig. 7. Plasma potential and anode discharge current (in A) as a function of time.

The analysis has been performed on a time scale corresponding to the low frequency oscillations (20 – 30 kHz). These oscillations have to be correlated to the time for the neutral species to fill up the channel after the ejection of the ions by the electrostatic field (“breathing” discharge effect).

6. Dynamic of electron – high frequency

The probes used to measure the characteristic of the electrons were also built to be used as antenna. We made coaxial probe in order to have a better ratio signal to noise. These probes have been calibrated in a range of 1 MHz to 1 GHz and also we observed the signal measured from a moving source to study the effect of the distance. Here we want to observe the range of 1 to 10 MHz because this bandwidth corresponds to the azimuthal drift of electrons.

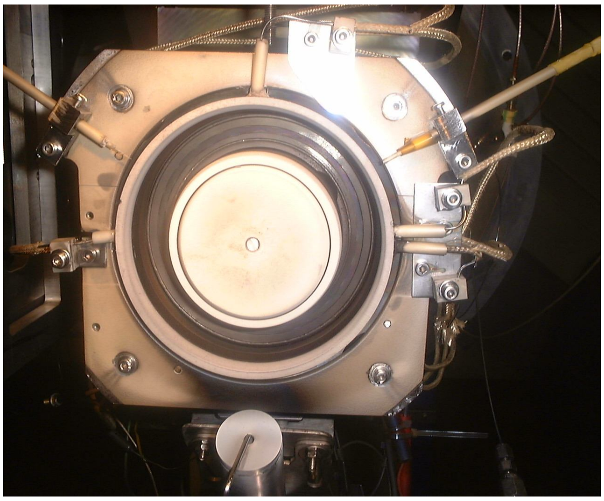

Fig. 8. Hall thruster with antenna and coaxial probes

A SPT-100-ML presents a middle radius about 4,225 cm and the electric field can be estimated about 10.10^4 V/m and the magnetic field about 150 G. Then the drift velocity can be estimated about:

$$v_D = \frac{E}{B} \approx \frac{2 \cdot 10^4}{150 \cdot 10^{-4}} = 1{,}33 \cdot 10^6 \text{ m/s}$$

The perimeter of the middle radius is of $26{,}5 \cdot 10^{-2}$ m, then we know the velocity and the distance, we can calculate a coarse time for an electron to do 1 circumference in the channel: $t_c \approx 2 \cdot 10^{-7}$ s. The fluctuation observed at this time scale tc corresponds of microwave of frequency 5 MHz. Therefore, it is interesting to study a bandwidth from 1 to 10 MHz which is associated to the azimuthal fluctuation of electrons inside the channel [3].

The method used, was to record the fluctuation of the floating potential of the probe. The advantage is that there is no electric system added which can disturb the measurement the probe. The probe is directly connected to the oscilloscope by a 50 Ω wire.

We record signal of the probe by a trigger on a high level of discharge current in order to synchronize the event with other parameters. Then we can correlate the observed phenomena with the discharge current.

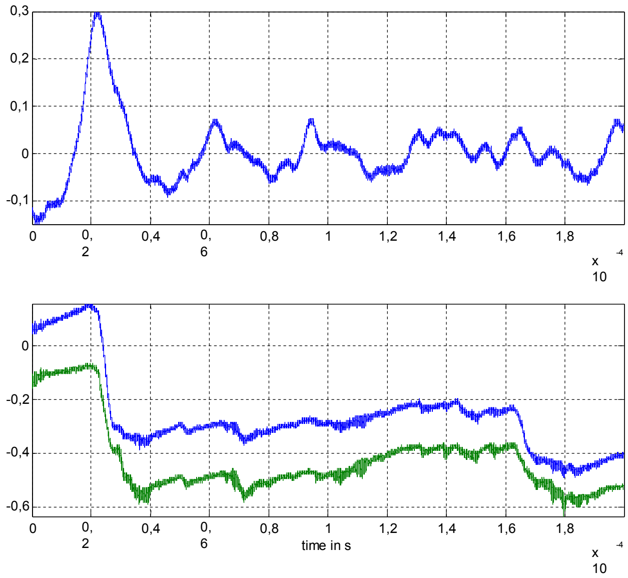

Fig. 9. Anode discharge current (alone), signal recorded by the probes A7 (blue) and A8 (green)

First, we noted that on each negative slope of the discharge current we observed high frequency on the probe. Then, there is a strong correlation between the low frequency 20 – 30 kHz of the discharge current and the high frequency of 1 – 10 MHz. The second remark is that we observed ultra short fall of floating potential associated with appearance of the high frequency. Then, if there is fluctuation of potential we can suppose there is fluctuation of electric field and consequently transport of light charged particles like electrons.

We can also correlate the appearance of high frequency instability with the result of electron density by the time resolved probe measurement. The maximum of electron density appears on the negative slope of anode discharge current as the instability. Then the both phenomena may be linked to the transport of electron across the magnetic barrier at the exit of the discharge channel.

All these remarks about appearance and dynamic of phenomena indicate us to use a time-frequency analysis of the signal.

We used a spectrogram function to analyse the probe's signal with the Matlab® scientific software.

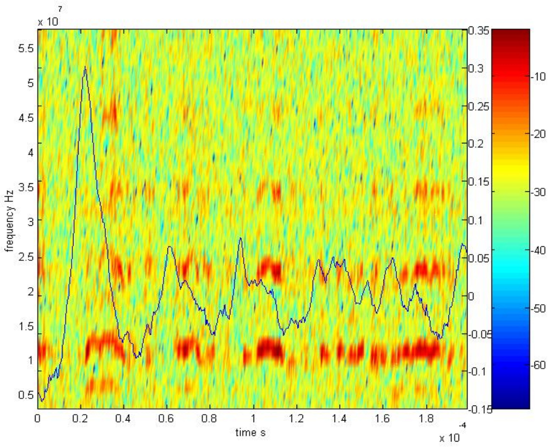

Fig. 10. Specgram (time-frequency dB) of A7 probe signal and anode discharge current oscillation (blue)

The specgram confirmed the first observed remarks about appearance of phenomena on the negative slope of discharge current. We also observed that the main peak is of 12 MHz and not at 5 or 6 MHz as we supposed. We may suppose that there is not only one rotating phenomena in azimutal direction but two or three. We can imagine 2 bursts of electrons rotating with the drift velocity of electron in the annular chamber at the exit plan of the thrusters where the magnetic barrier is strong.

At this time, the analysis of signal for varying parameters as magnetic field or potential discharge carries on [4] but the analysis of frequency dynamic presents a problem. The signals are non-stationary and the time scale resolution is shorter than the window used by the specgram function of Matlab®. Then we have to use another method of signal analysis which takes into account the non-stationarity and non linearity of signal to study the dynamic of this phenomenon.

Diode regime and high frequency studies have been done with Prof. A.Bouchoule, Dr. A. Lazurenko and V. Vial.

Conclusion

The presented results contribute to improve the knowledge of the ion dynamics, cathode properties and low and high frequencies oscillations of HET. They are complementary of other measurements as optical emission measurements, CCD camera, analyser of the ion energy and LIF used by another way in the other French laboratories working in the French research Group.

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