

Time-resolved measurements of plasma properties in the far-field plume of a low-power Hall effect thruster

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Abstract – Time-resolved measurements of the plasma parameters are performed in the far-field plume of a low-power Hall effect thruster with permanent magnets. The plasma potential is measured with a cylindrical Langmuir probe and an emissive probe, the electron temperature and the electron density are measured with a cylindrical Langmuir probe. The thruster discharge is maintained in a harmonic oscillation regime to guarantee repeatable conditions for all measurements.

Nomenclature

D_a	anode mass flow rate [mg/s]
f	frequency [Hz]
I_d	discharge current [A]
n_e	electron density [m^{-3}]
T_e	electron temperature [eV]
U_d	discharge voltage [V]
V_p	plasma potential [V]
x	axial direction [mm]
y	radial direction [mm]

I. Introduction

Electric propulsion is at present a well established technology for space applications [1]. In comparison with chemical rocket jets, electric propulsion devices offer an attractive way to save propellant mass thanks to a much faster propellant ejection speed. Among all electric propulsion devices, Hall effect thrusters (HET) are currently recognized as an attractive propulsion means for long duration missions and maneuvers that require a large velocity increment. They are used for geosynchronous satellite attitude control and station keeping [2, 3]. As demonstrated by the successful SMART-1 moon flyby mission, HETs can also be used as primary propulsion engine for orbit transfer maneuvers [4].

The basic physics of a Hall thruster consists of a magnetic barrier in a low pressure DC discharge

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maintained between an external cathode and an anode [2, 3]. The anode, that also serves as gas injector, is located at the upstream end of a coaxial annular dielectric channel that confines the discharge. Xenon is generally used as working gas for its specific properties in terms of atomic mass and low ionization energy. A set of either solenoids or magnets provides a radially directed magnetic field of which the strength is maximum in the vicinity of the channel exit. The magnetic field is chosen strong enough to make the electron Larmor radius much smaller than the discharge chamber sizes, but weak enough not to affect ion trajectories. The electric potential drop is mostly concentrated in the final section of the channel owing to the high electron resistivity. The corresponding local axial electric field drives a high azimuthal drift - the Hall current - that is responsible for the efficient ionization of the supplied gas. It also accelerates ions out of the channel, which generates thrust. The ion beam is neutralized by a fraction of electrons emitted from the cathode.

The plasma plume of Hall effect thrusters exhibits a relatively large divergence angle of about 45° [5]. A concern in the use of these devices is therefore the possible interaction between the plasma plume and the host spacecraft [6]. Although the plume is quasineutral, it still consists of charged particles, which leads to electrical and mechanical interactions with the spacecraft. It is thus important to develop and improve models of the plume in order to help assessing the spacecraft integration issues. The numerical models of the thruster plume need to be validated by comparison with experimental data. Therefore the entire plasma plume needs to be mapped to obtain ion, electron and neutral properties.

The global dynamic of the discharge being controlled by the electrons, it is thus interesting to investigate the electron temperature T_e , the electron number density n_e as well as the plasma potential V_p in the plume of a Hall effect thruster. The plasma in a Hall thruster is proved to be strongly non-stationary. Time-averaged measurements of the plasma parameters can give a first estimate of the plasma properties. However, time-resolved measurements are needed to correctly measure the time-correlated plasma properties.

In this contribution, we present time-resolved measurements of the plasma potential, the electron temperature as well as the electron density measured in the far-field plume of the 200 W permanent magnet PPI (acronym for small innovative thruster: “Petit Propulseur Innovant”) Hall thruster fired at a discharge voltage of 225 V and a anode mass flow rate of 1.0 mg/s [7]. The thruster discharge is forced into a harmonic, low-frequency oscillation regime by applying a sinusoidal modulation on a floating electrode in the vicinity of the cathode. The frequency of this modulation has to be tuned to a plasma resonance in order to achieve the harmonic regime of the thruster. With the thruster operating in a harmonic regime, proper time-resolved measurements can be carried out, as the frequency content will be the same for all measurement points. The plasma potential is measured with a cylindrical Langmuir and a heated emissive probe. The electron temperature and density are measured with a cylindrical Langmuir probe. The three parameters are measured at 6 different positions in the far-field plume. In Sec. II., the experimental set-up is described and the time-resolved measurement technique is introduced. Sec. III. shows the influence of the modulation on the thruster parameters as well as on the plasma parameters. The time evolution of V_p , T_e and n_e is shown and discussed for two oscillation frequencies. Time-averaged values computed from the time-resolved data are compared to direct time-averaged measurement outcomes. Furthermore the time evolution of V_p obtained with the Langmuir probe and the emissive probe is compared. Finally, a conclusion is given in Sec. IV..

II. Experimental set-up

A NExET

The experiments were carried out in the ground-test facility NExET . The vacuum chamber is 1.8 m long and 0.8 m in diameter. It is equipped with a large dry pump, a 200 l/s turbomolecular pump and a cryogenic pump with a typical surface temperature of 30 K. A background pressure of 2×10^{-5} mbar is achieved with a xenon mass flow rate of 1.0 mg/s and an input power of 250 kW [7]. The thruster can be mounted onto two moving stages to allow a displacement in both the axial (x) and radial (y) direction.

B PPI Hall thruster

The PPI thruster is a 200 W Hall effect thruster able to deliver a thrust of about 10 mN at a discharge voltage of 250 V and a mass flow rate of 1.0 mg/s [8]. This low-power Hall thruster exhibits three interesting features [9, 10]. First, the magnetic field is provided by small SmCo magnets. The magnetic field strength can easily be varied by changing the number of magnets. Second, the gas is homogeneously

injected through a porous ceramic instead of a classical metal hollow gas injector. A stainless steel ring placed at the end of the channel serves as anode. Third, a central copper heat drain and a radiator are used to reduce the thermal heat load. The PPI thruster used in the present study has another interesting feature: The channel width can be varied while keeping the mean diameter and the channel length constant [7]. The experiments were done with the largest channel, the so called 3S₀ configuration. The channel walls were made of alumina. A heated cathode, provided by MIREA, was used with a cathode mass flow rate of 0.2 mg/s. Xenon was used as working gas for the thruster and the cathode.

C Probes

A single cylindrical Langmuir probe was used to characterize the far-field plume of the PPI thruster. The Langmuir probe was made of a 0.38 mm in diameter tungsten wire. The non-collecting part of the wire was insulated from the plasma by a 100 mm long and 2 mm in diameter alumina tube. The length of the collecting part was 5 mm. The voltage sweep and the resulting probe current measurement were performed using the ALP SystemTM manufactured by Impedans. The parameters V_p , T_e and n_e were derived from the probe characteristics using the standard thin-sheath probe theory assuming a maxwellian electron distribution function [11].

The plasma potential was also measured using a floating emissive probe. The emitting part of the probe consisted of a 8 mm long loop of 150 μ m in diameter thoriated tungsten wire. The ends of the wire were mechanically crimped to copper wires and inserted into two parallel holes of a 100 mm long and 4 mm in diameter alumina tube. The filament was heated with a DC power supply up to the regime of electron emission. In the ideal case the floating potential of a sufficiently emitting probe is equal to the plasma potential. In this case the electron current is completely compensated by the emission current from the probe, therefore no net current flows through the probe and there is no sheath around the probe [12]. However the electrons emitted by the probe are usually colder than the electrons in the plasma. The space charge of the cold emitted electrons causes a saturation of the sheath around the hot filament and therefore the measured probe potential is not exactly equal to the plasma potential [13]. If the temperature of the plasma electrons is large compared to the temperature of the emitted electrons, the plasma potential measured with the emissive probe is underestimated. If the emitted electrons and the plasma electrons have approximately the same temperature, the value of the plasma potential measured by the emissive probe is overestimated. A typical measurement of the probe potential as a function of the heating current is depicted in Fig. 1. As can be seen in Fig. 1, the probe potential never really saturates but the slope clearly extenuates if the current is increased above 4 A. This has already been observed in other thrusters and plasma sources [13, 14]. For the measurement of the plasma potential in the far-field, the heating current was fixed to 4.3 A. The lifetime of the emissive probe in the far-field was in the order of several hours allowing a complete mapping of the far-field with one probe.

The two types of probes were fixed next to each other in the far-field of the PPI thruster. As the thruster was mounted onto two moving stages, V_p , T_e and n_e could be measured at different positions in the far-field plume.

D Time-resolved measurements

In order to perform proper time-resolved measurements, the thruster needs to be maintained in a harmonic oscillation regime. This has two main advantages: First, the harmonic signal can be used as trigger signal for time-resolved measurements, hence no need for a fast power switch that perturbs the thruster behaviour [15]. Second, the thruster behaviour is stationary. The frequency content is therefore the same at any time, which warrants repeatable measurements. Furthermore time series can be added up without propagating noise and error.

To achieve a harmonic operating regime of the PPI thruster, a sinusoidal modulation with a tuneable frequency is applied between a floating electrode and the negative pole of the cathode heating circuit. A schematic view of the electrical set-up is represented in Fig. 2. The frequency cannot be chosen randomly, it has to be one of the resonance frequencies of the discharge. The keeper is only used for the thruster ignition. After the ignition the keeper represents solely a floating electrode in the plasma and can be therefore used to apply the modulation. The modulation signal is provided by a function generator and amplified to achieve a peak-to-peak value of about 100 V. The modulation signal is applied by way of an isolation transformer to keep the keeper and the cathode insulated from ground. The transformer can be placed at two different positions in the electrical set-up: either between the amplifier and the keeper/cathode line, or between the function generator and the amplifier. It might be necessary to increase the current driven to the keeper in order to force the thruster to be in a harmonic regime. In

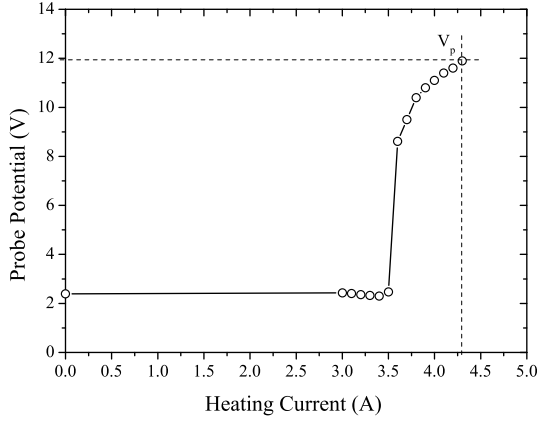


Fig. 1: Emissive probe potential against the heating current in the far-field plume of the PPI thruster.

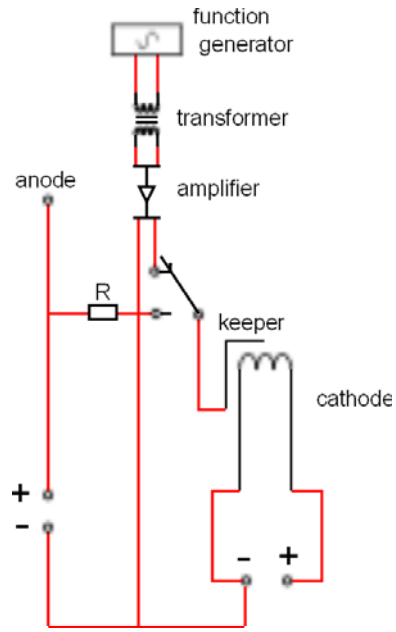


Fig. 2: Schematic view of the electrical set-up of the keeper modulation.

this case the isolation transformer should be placed between the function generator and the amplifier, as the amplifier has a lower output impedance ($200\ \Omega$) than the transformer ($2\ \text{k}\Omega$). However, in this configuration the amplifier has to stand the driven current and it should be protected against the current that is delivered to the keeper at the thruster ignition, this current is similar to the discharge current, i.e. about 1 A for the PPI thruster. The frequency of the modulation signal has to be adapted to achieve a harmonic operation regime of the thruster. The square wave output of the function generator is used as trigger signal for the ALP system in time-resolved mode. The current driven to the keeper is below 10 % of the discharge current and therefore negligible.

The ALP system provides a time-resolved option. In this mode the probe current is recorded over one period of the trigger signal for a fixed bias voltage of the probe. This procedure is repeated for all the necessary voltage steps in order to reconstruct the current-voltage characteristics for every time step. In the presented work, the time resolution was set to $1\ \mu\text{s}$ and acquisition was averaged over 1000 steps.

The time evolution of the probe potential of the cold and the heated emissive probe were recorded simultaneously to the discharge current oscillations. The power supply for the probe heating was powered via a UPS in order to reduce the capacity against ground. If this capacity is too high, the oscillations of the probe potential cannot be observed as the capacity together with the inner resistance of probe form a low-pass filter. The bandwidth of this configuration is about 60 kHz.

III. Results

The measurements of the plasma parameters in the far-field plume are presented for the PPI thruster operating at a discharge voltage of $U_d = 225\ \text{V}$ and an anode mass flow rate of $D_a = 1.0\ \text{mg/s}$. The mean discharge current is $I_d = 0.92\ \text{A}$. The probe measurements are done at two different axial positions ($x = 150$ and $200\ \text{mm}$) and three different radial positions ($y = 0, 25$ and $50\ \text{mm}$), where $x = 0\ \text{mm}$ corresponds to the thruster exit plane and $y = 0\ \text{mm}$ corresponds to the thruster axis. A comparison of the mean discharge current and the discharge current oscillations for different probe positions in the plume reveals that the probes position has no influence on the discharge behavior.

A Influence of the keeper modulation on the operating parameters

As has been mentioned before, in order to perform proper time-resolved measurements, the thruster needs to be in a harmonic regime. Fig. 3 represents the time evolution of the discharge current and the plasma potential as a function of the modulation frequency. The plasma potential is measured with a heated emissive probe. The time-evolution of I_d and V_p is recorded at 200 mm downstream the thruster

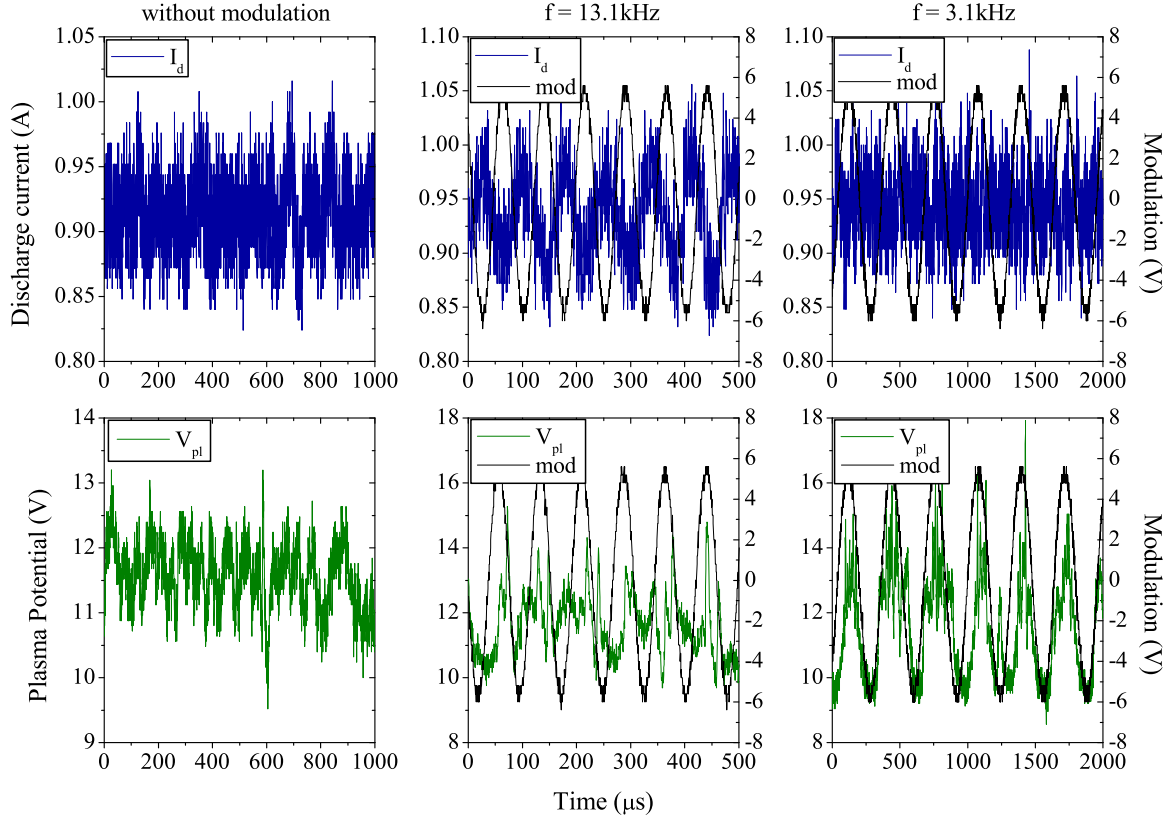


Fig. 3: Influence of the modulation on the discharge current I_d (first row) and the plasma potential V_p measured with a heated emissive probe (second row). First column column represents the time evolution of I_d and V_p without modulation, second column for a modulation at 13.1 kHz and third column for a modulation frequency of 3.1 kHz. The displayed modulation is the signal from the function generator before amplification.

exit plane ($x=200\text{ mm}$) on the thruster axis ($y=0\text{ mm}$). The represented modulation signal is the signal from the function generator before amplification. As can be seen in Fig. 3, without a modulation signal, the discharge current I_d is non-stationary and one cannot distinguish a dominant frequency in the discharge current time series, whereas for a modulation frequency of 13.1 kHz the discharge current is fairly well synchronized to the modulation waveform. The amplitude is not constant, but the oscillation frequency is constant. At a modulation frequency of 3.1 kHz, one can distinguish a slight synchronization of I_d to the modulation signal, but there are higher frequencies superimposed to the modulation frequency. However the influence of the modulation on the mean discharge current is very weak ($\bar{I}_d = 0.92 \pm 0.01\text{ A}$). The second row of Fig. 3 shows that the behaviour for the plasma potential is not the same. Without modulation no correlation between V_p and the modulation signal can be distinguished. For a modulation frequency of 13.1 kHz, the time evolution of V_p is influenced by the modulation but no synchronization can be achieved. Contrary to the discharge current, the plasma potential can be stabilized to one frequency if the modulation frequency is set to 3.1 kHz.

B Time-resolved measurements

As has been shown in Part A, the behaviour of the discharge current and the plasma potential measured with heated emissive probe are different for the same frequency of the modulation signal. In order to evaluate the time evolution of the plasma potential, the electron temperature and the electron density, time-resolved measurements are performed with the cylindrical Langmuir probe at 6 different positions in the plume. The time-dependent current-voltage characteristics are recorded with a time resolution of $1\text{ }\mu\text{s}$ over one period. For every characteristic, the bias voltage is swept from -40 to 40 V . Each characteristic

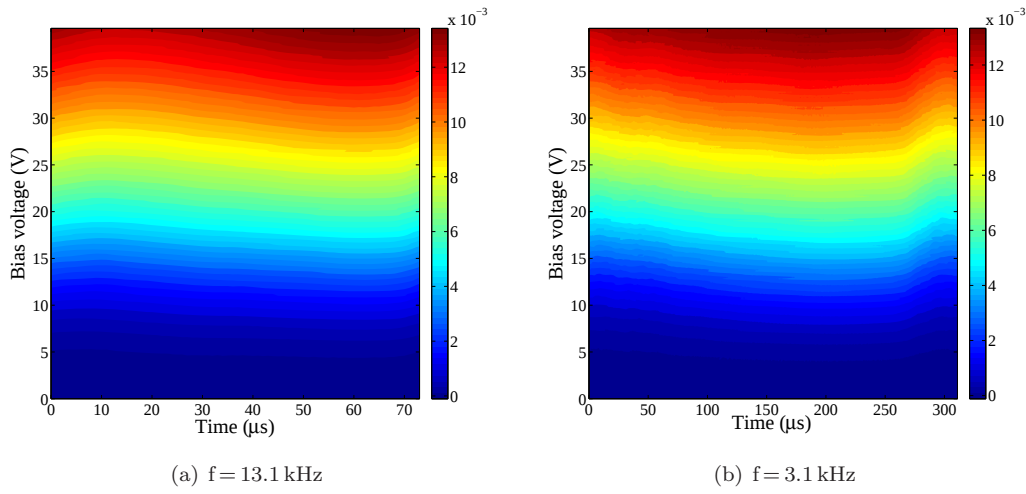


Fig. 4: Time-dependent current voltage characteristic recorded with the cylindrical Langmuir probe at $x = 150$ mm and $y = 0$ mm in the plume of the PPI operating at $U_d = 225$ V and $D_a = 1.0$ mg/s. The frequency of the keeper modulation is 13.1 kHz and 3.1 kHz respectively. The colorbar gives the value of the probe current in A.

is an average over 1000 acquisitions. An example of the time-dependent current-voltage characteristic is represented in Fig. 4. As the differences are more pronounced in the electron current branch of the characteristic, only the part for a bias voltage above 0 V is shown. The time evolution of V_p , T_e and n_e for the two different modulation frequencies is displayed in Fig. 5 over one oscillation period. The first row represents the evolution over one period at 13.1 kHz, the second row the one for 3.1 kHz. The measurements are done at 150 mm downstream the thruster exit plane and 25 mm off the thruster axis.

As can be seen in Fig. 5, the time evolution is different for V_p , T_e and n_e . There is also a difference between the results for the two different frequencies. The time evolution of the electron density at $f = 13.1$ kHz is almost sinusoidal, whereas the time evolution for $f = 3.1$ kHz is almost rectangular. Nevertheless, one can distinguish a high frequency oscillation superimposed to the basic rectangular waveform. The frequency of this superimposed oscillations is about 13 kHz. However for both frequencies the fluctuations are very weak, i.e. approximately 7 % of the mean value. The time evolution of V_p and T_e is roughly similar for the two frequencies, i.e. a sharp increase at the beginning of the cycle followed by a slow decrease. For both frequencies a higher frequency oscillation is superimposed to the basic oscillation. The frequencies are different for the two modulation frequencies: about 63 kHz for $f = 13.1$ kHz and 55 kHz for $f = 3.1$ kHz. These high frequency oscillations are repeatable as every characteristic is averaged over 1000 acquisitions. The fluctuations of V_p and T_e are significantly higher for 3.1 kHz than for 13.1 kHz, i.e. 33 % against 13 % for the plasma potential and 17 % against 54 % for the electron temperature.

The evolution in time (over one modulation period) and space (radial direction) of the plasma potential, the electron temperature and the electron density for two different positions downstream the thruster exit plane is exemplified in Fig. 6 and Fig. 7 for the two different modulation frequencies. The radial profile is interpolated from the three recorded radial positions. The plotted data is unsmoothed. The structure of the fluctuations that can be observed in the example trace in Fig. 5 can also be seen in the different maps represented in Fig. 6 and Fig. 7. One can see that V_p , T_e and n_e decrease with an increasing distance from the thruster exit plane (axial direction) and from the thruster axis (radial direction).

The time evolution of the plasma potential is also measured using the emissive probe. The plasma potential is assumed to be the floating potential of the emissive probe heated with a current of 4.3 A. The time evolution of the plasma potential is recorded simultaneously to the discharge current for the two different modulation frequencies. An example trace of the plasma potential as a function of the modulation frequency is represented in Fig. 3. The evolution in time (over one period) and space (radial direction) is shown in Fig. 8 and Fig. 9 for two different axial positions. The radial profile is interpolated from the three measured positions. The time evolution of the plasma is a snapshot for a single oscillation cycle, no averaging over several periods is carried out. For 3.1 kHz one can also observe the high frequency oscillations that are superimposed to the modulation frequency. However, the amplitude of these oscillations is higher for the emissive probe measurements than for the Langmuir probe measurements. The

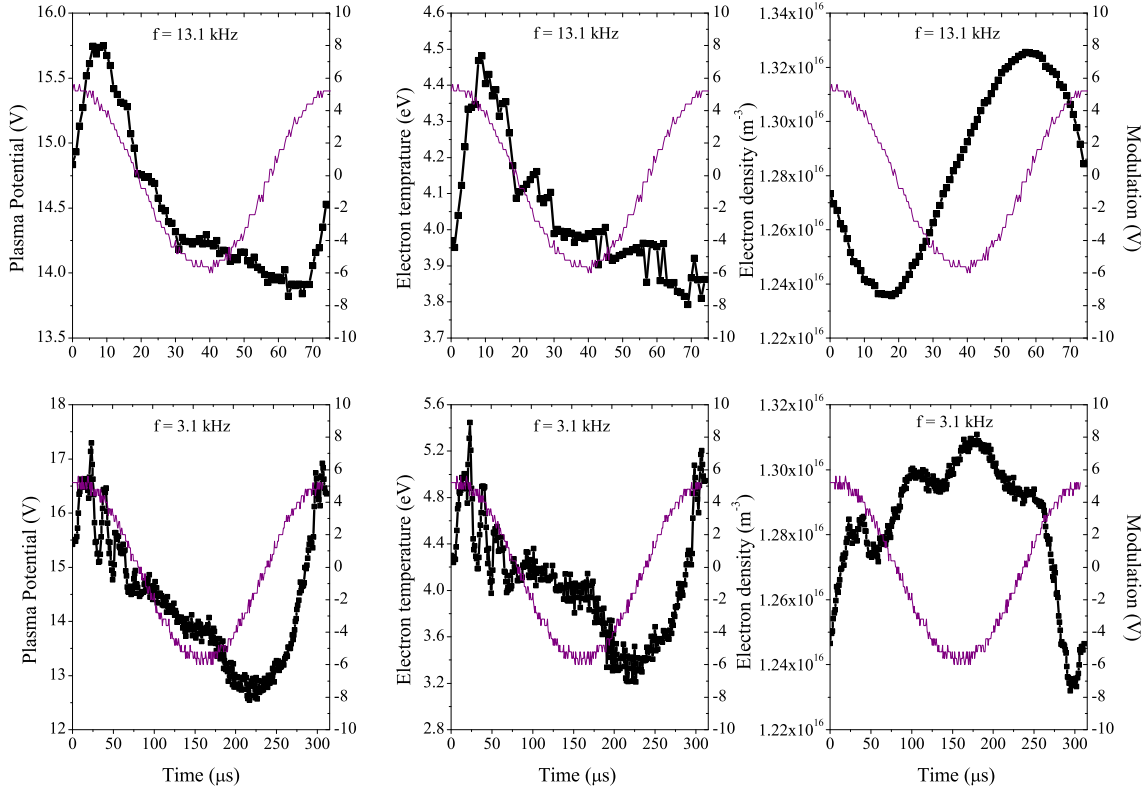


Fig. 5: Time evolution of plasma potential V_p , electron temperature T_e and electron density n_e measured with a Langmuir probe at $x = 150$ mm and $y = 25$ mm in the plume of the PPI operating at $U_d = 225$ V and $D_a = 1.0$ mg/s. The frequency of the keeper voltage modulation is 13.1 kHz, respectively 3.1 kHz. The displayed modulation is the signal from the function generator before amplification.

mean value of V_p measured with the emissive probe is lower than the one measured with the Langmuir probe. This fact can be explained by the underestimation of V_p due to the fact that the plasma electron temperature is higher than the temperature of the electrons emitted by the emissive probe, see e.g. [13].

C Comparison of time-resolved and time-averaged measurements

The plasma in a Hall effect thruster is proved to be highly non-stationary. Hence, time-resolved measurements of the plasma parameters should be performed in order to get more accurate results. The current-voltage characteristic of a Langmuir probe is not linear. Hence a time averaged measurement of the plasma parameters with a Langmuir probe is expected not to give the correct values. In order to evaluate the difference between time-averaged and time-resolved measurements, the mean value of the time-dependent plasma parameters (V_p , T_e and n_e) is compared to the value obtained from time-averaged Langmuir probe measurements. The time-averaged measurements are performed for the same operating conditions and at the same positions in the plume as the time-resolved measurements. The floating electrode close to the cathode is again modulated at 3.1 kHz and 13.1 kHz. One time-averaged measurement is also performed without a modulation at $x = 200$ mm and $y = 50$ mm. As can be seen in Fig.10, the values from the time-averaged measurements are different from the mean values of the time-resolved measurements. The difference is more pronounced for V_p and T_e , the difference is almost negligible for n_e . The difference is more pronounced for $x = 150$ mm than for $x = 200$ mm. The values of V_p and T_e obtained by time-averaged values are different for the two different modulation frequencies. Although the time evolution is different for the two frequencies, the mean values of the time-resolved measurements are almost the same for the two frequencies. The values of V_p , T_e and n_e measured without modulation are similar to the mean values measured with the modulation. One can therefore assume that

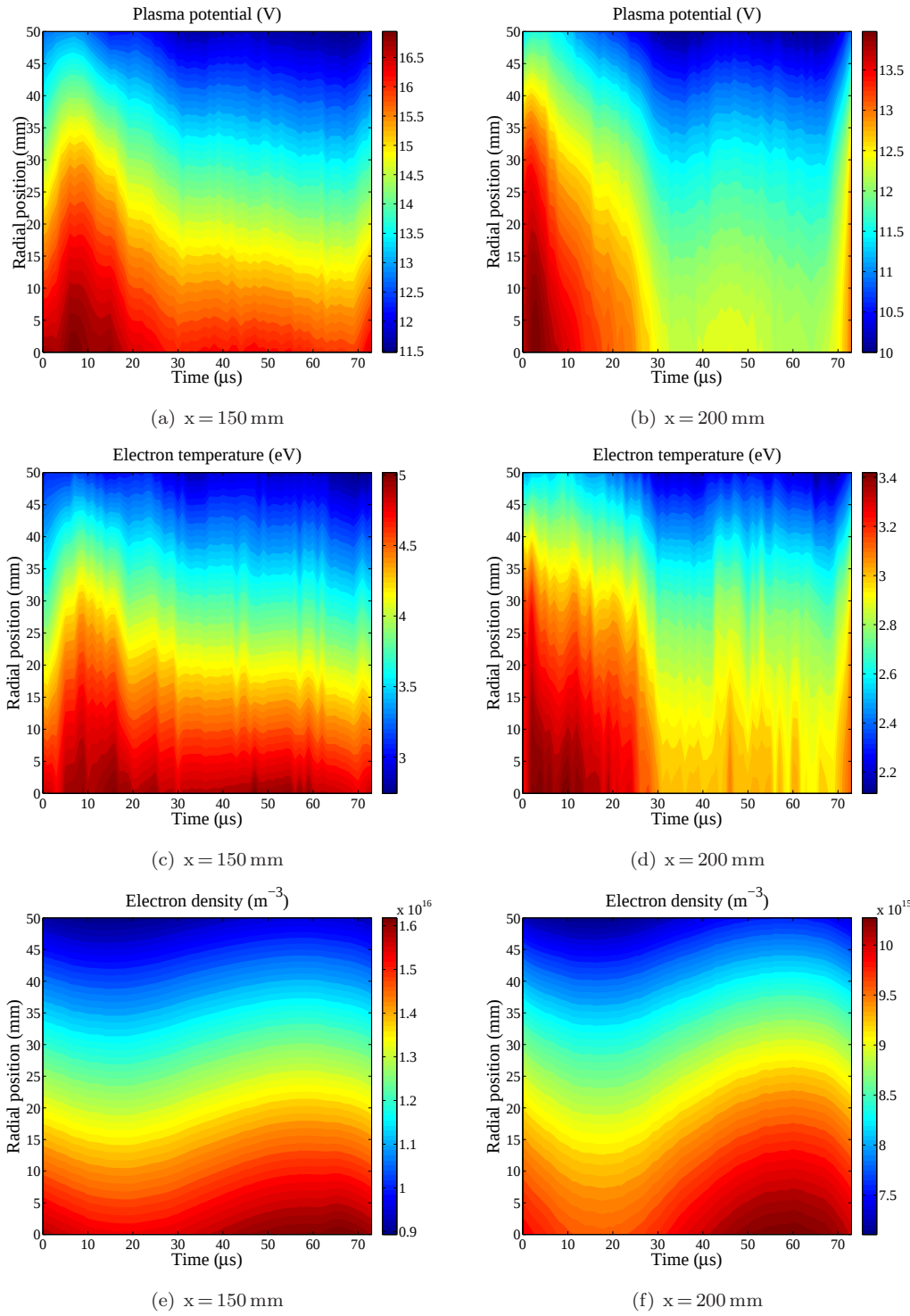


Fig. 6: Evolution in time and space (radial direction) of V_p , T_e and n_e at two different distances from the thruster exit plane for the modulation frequency of $f = 13.1$ kHz.

the global behaviour of the discharge is not changed when the thruster is forced to a harmonic regime.

IV. Conclusion

In this contribution, time-resolved measurements of the plasma potential, the electron temperature and the electron density in the far-field plume of a low power Hall effect thruster are presented. A cylindrical Langmuir probe is used to measure V_p , T_e and n_e , V_p is also measured with an emissive

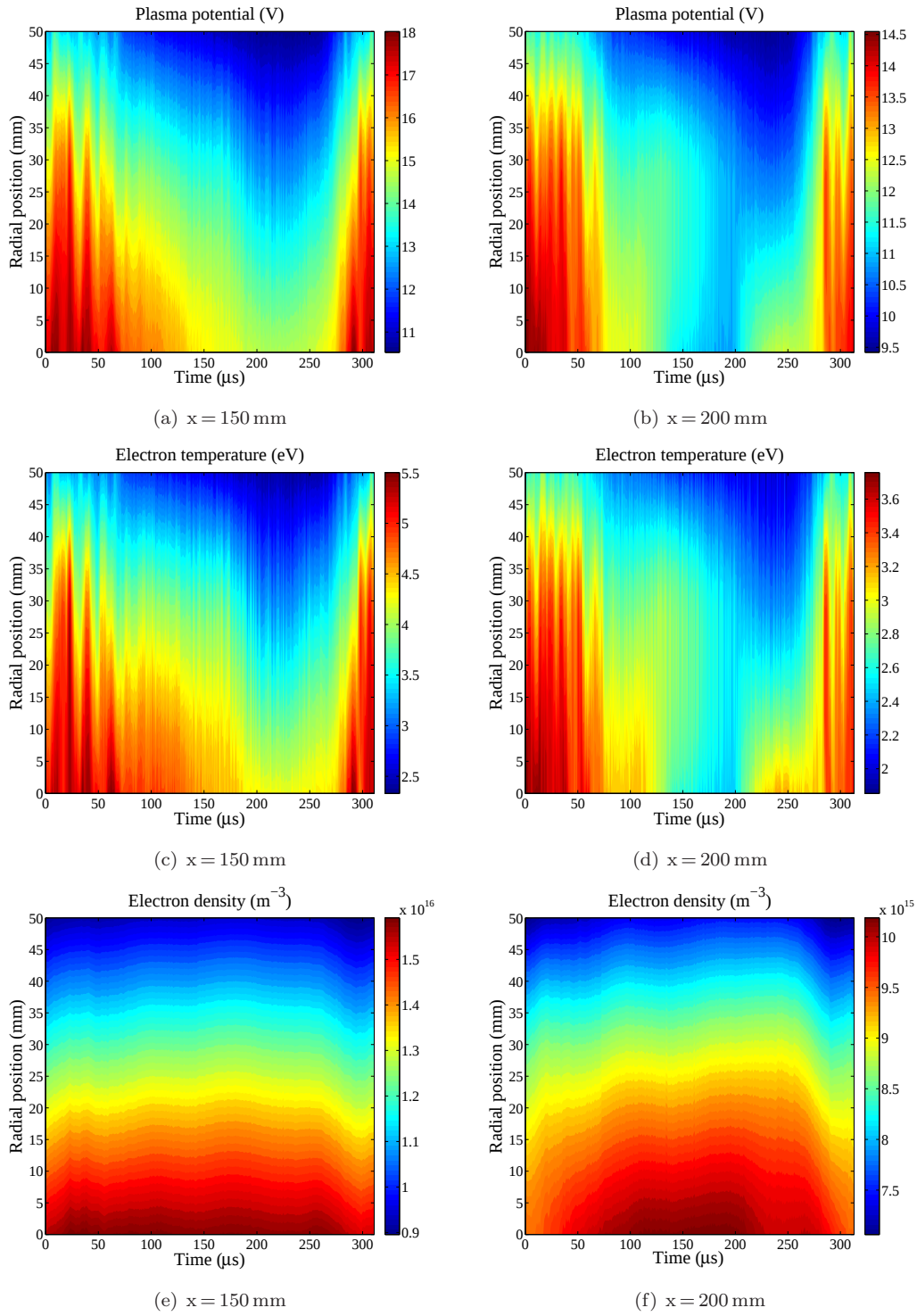


Fig. 7: Evolution in time and space (radial direction) of V_p , T_e and n_e at two different distances from the thruster exit plane for the modulation frequency of $f = 3.1$ kHz.

probe. In order to do proper time-resolved measurements, the thruster is forced to an almost harmonic regime by applying a sinusoidal modulation to a floating electrode in the vicinity of the cathode. The frequency of this modulation is adjusted to obtain a stable operating regime of the thruster synchronized to the modulation. The frequency required for thruster synchronization is different whether the discharge current is observed or if one observes the plasma potential measured with a sufficiently heated emissive probe. The time evolution of V_p , T_e and n_e over one period is different for the two modulation frequencies. However, the mean values are almost the same. On the contrary, a comparison of the mean values of V_p , T_e and n_e obtained from the time-resolved measurements with the values of the same plasma parameters

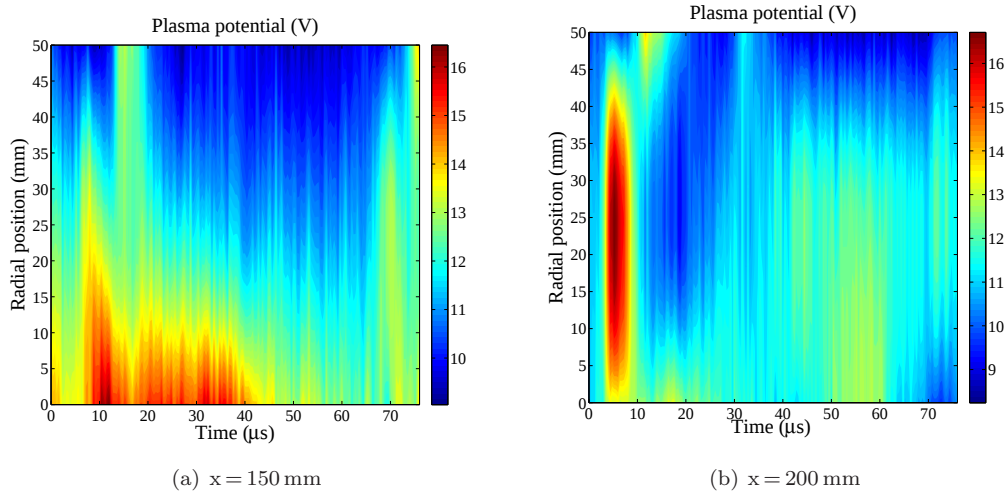


Fig. 8: Evolution in time and space (radial direction) of V_p measured with the heated emissive probe at two different distances from the thruster exit plane for the modulation frequency of $f = 13.1$ kHz.

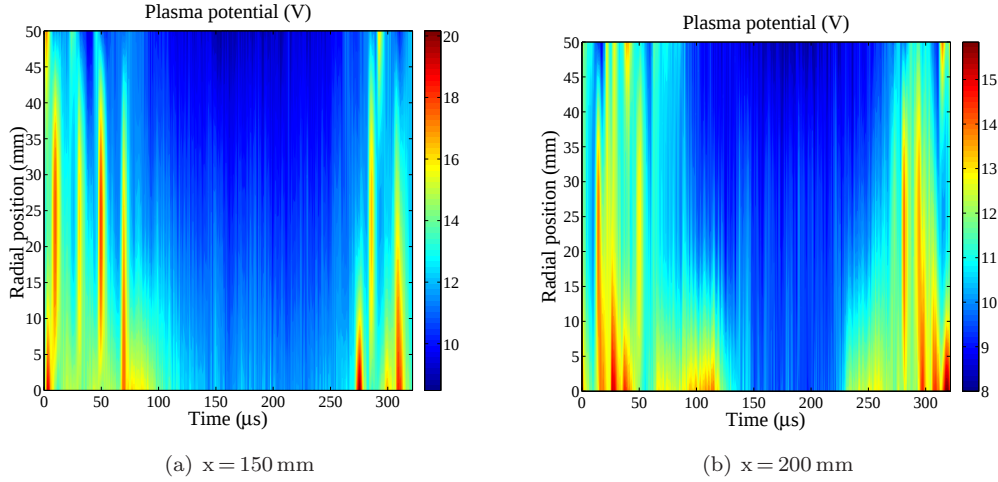
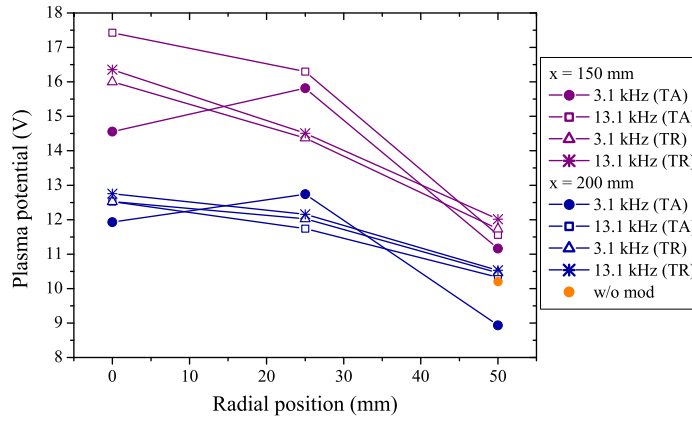


Fig. 9: Evolution in time and space (radial direction) of V_p measured with the heated emissive probe at two different distances from the thruster exit plane for the modulation frequency of $f = 3.1$ kHz.

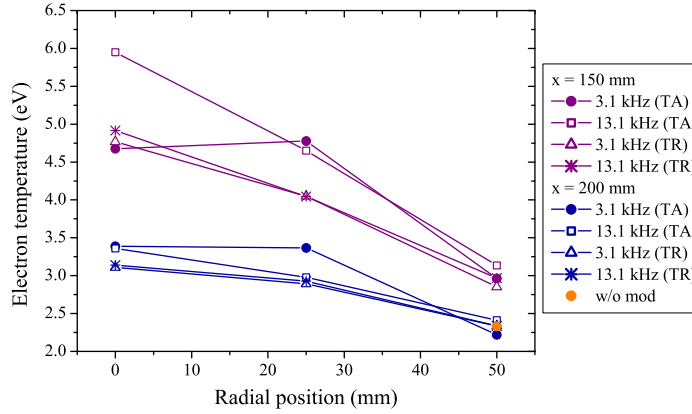
from time-averaged measurements revealed that they do not match. The most probable reason for this discrepancy is the non-linearity of a Langmuir probe current-voltage characteristic. Fluctuations of the plasma parameters in a non-stationary plasma can therefore affect the time-averaged measurements. As the plasma in a Hall effect thruster is proved to be strongly non-stationary, time-resolved measurements are necessary to get accurate measurements of the plasma parameters.

Acknowledgments

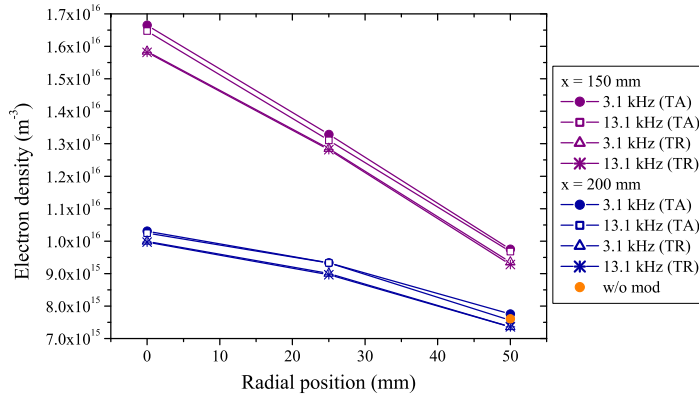
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(a) Plasma potential



(b) Electron temperature



(c) Electron density

Fig. 10: Comparison of time-resolved (TR) and time-averaged (TA) measurements in the plume of the PPI thruster operating at $U_d = 250$ V and $D_a = 1.0$ mg/s.

References

- ¹ Frisbee R.H., “Advanced Space Propulsion for the 21st Century”, *J. Propulsion Power*, Vol. 19, No. 6, 2003, pp. 1129-1154.

- ² Zhurin V.V., Kaufmann H.R., Robinson R.S., “Physics of Closed Drift Thrusters”, *Plasma Sources Sci. Technol.* Vol. 8, 1999, pp. R1-R2.
- ³ D. M. Goebel, I. Katz, *Fundamentals of Electric Propulsion*, Wiley, Hoboken, NJ, 2008.
- ⁴ C.R. Koppel, F. Marchandise, M. Prioul, D. Estublier, F. Darnon, “The SMART-1 Electric Propulsion Subsystem Around the Moon: In Flight Experience”, *Proceedings of the 41th Joint Propulsion Conference*, Tucson, Arizona, AIAA paper 05-3671, 2005.
- ⁵ R. R. Hofer, R. S. Jankovsky, A. D. Gallimore, “High-Specific Impulse Hall Thruster, Part 1: Influence of Current Density and magnetic field”, *J. Propul. Power*, Vol. 22, No. 4, 2006, pp. 721-731.
- ⁶ F. Darnon 2000, “Plume Effects in Plasma Propulsion, An Overview of CNES Activities” *Proceedings of the 3rd International Conference on Spacecraft Propulsion*, Cannes, France ESA SP-465, 2000.
- ⁷ A. Lejeune, K. Dannenmayer, G. Bourgeois, S. Mazouffre, M. Guyot, S. Denise, “Impact of the channel width on Hall thruster discharge properties”, *Proceedings of the 32nd International Electric Propulsion Conference*, Wiesbaden, Germany, IEPC paper 2011-019, 2011.
- ⁸ A. Leufroy, T. Gibert, A. Bouchoule, “Characteristics of a Permanent Magnet Low Power Hall thruster”, *Proceedings of the 31th International Electric Propulsion Conference*, Ann Arbor, Michigan, paper 09-083, 2009.
- ⁹ M. Guyot, P. Renaudin, V. Cagan, C. Boniface, patent FR 07 05658, 2007.
- ¹⁰ M. Guyot et al., “New Concepts for Magnetic Field Generation in Hall Effect Thrusters”, *Proceedings of the 5th International Spacecraft Propulsion Conference*, Heraklion, Greece, 2008.
- ¹¹ P. M. Chung, L. Talbot, K. J. Touryan, *Electric Probes in Stationary and Flowing Plasmas: Theory and Application* Springer-Verlag New York Inc., 1975.
- ¹² C. Ionita et al., “The Use of Emissive Probes in Laboratory and Tokamak Plasmas” *Contrib. Plasma Phys.*, Vol. 51, No. ,2-3, 2011, pp. 264-270.
- ¹³ A. Marek, M. Jílek, I. Picková, P. Kudrna, M. Tichý, R. Schrittwieser, C. Ionita, “Emissive Probe Diagnostics in Low-Temperature Plasma - Effect of Space Charge and Variations of Electron Saturation Current”, *Contrib. Plasma Phys.*, Vol. 48, No. 5-7, 2008, pp. 491-496.
- ¹⁴ A. W. Smith, M. A. Cappelli “Time and Space-correlated Plasma Property Measurements in the Near-field of a Coaxial Hall Discharge”, *Phys. Plasmas*, Vol. 16, No. 7, 2009, pp. 073504.
- ¹⁵ S. Mazouffre, G. Bourgeois, “Spatio-temporal characteristics of ion velocity in a Hall thruster discharge”, *Plasma Sources Sci. Technol.*, Vol. 19, 2010, pp. 065018.