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Time-Resolved Measurements of Plasma Properties Using Electrostatic Probes in the Cross-Field Discharge of a Hall Effect Thruster

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Time-resolved measurements of the plasma parameters are performed in the plume of a cross-field discharge. The plasma potential is measured with a cylindrical Langmuir probe and an emissive probe. The electron temperature and density are measured with a cylindrical Langmuir probe. The cross-field discharge is maintained in a harmonic oscillation regime to guarantee reproducible conditions for all measurements.

1 Introduction

Cross-field discharges are often encountered in the field of plasma physics, for example in Hall effect thrusters for spacecraft propulsion [1], in magnetized plasma columns for fundamental studies of turbulence and instabilities [2], in End-Hall ion sources for plasma processing and coating formation [3], in the edge and the divertor region of a Tokamak reactor [4] and in the magnetic filter region of negative ion sources for neutral beam generation [5]. The present work focuses on Hall effect thrusters.

The basic physics of a Hall thruster consists of a magnetic barrier in a low pressure DC discharge maintained between an external cathode and an anode [1]. 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 used as working gas for its specific properties in terms of atomic mass and low ionization energy. A set of solenoids or permanent 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 in a Hall thruster is proved to be strongly non-stationary with many types of oscillations. Plasma and discharge instabilities in the 1 kHz to 60 MHz frequency range have been observed during operation of Hall effect thrusters [6, 7]. It is important to notice that in this context “instability” does not mean “unstable operation”. In fact not all oscillations are disadvantageous, natural discharge and plasma instabilities play major roles in ionisation, particle diffusion and acceleration processes. However, if these plasma oscillations become uncontrolled, they can cause a decrease of the thruster performances, they can damage electric power supplies and they can even provoke the extinction of the discharge [6]. The power spectrum of discharge and plasma instabilities in a Hall effect thruster is dominated by low-frequency oscillations in the kHz range, the so-called breathing

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mode [8,9]. Time-resolved measurements of the plasma parameters are necessary to account for temporal fluctuations of these parameters. The transient behavior of ions in the plume has already been well characterized using different measurement techniques [10–12]. As the global dynamic of the discharge is controlled by the electrons, it is interesting to also investigate the temporal behavior of the electrons. Recently, the temporal behavior of electron properties in the near- and far-field plume of a Hall effect thruster has been investigated using electric probes [13–15].

In this contribution, we present time-resolved measurements of the plasma potential V_p, the electron temperature T_e as well as the electron density n_e in the far-field plume of a 200 W permanent magnet Hall thruster fired at a discharge voltage of 225 V and an anode mass flow rate of 1.0 mg/s [16]. The main feature here is that 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. With the thruster operating in an almost harmonic regime, proper time-resolved measurements can be carried out, as the discharge current frequency content does not change in time. The plasma potential is measured with a cylindrical Langmuir and a heated emissive probe. The electron temperature and the electron density are measured using a cylindrical Langmuir probe. A review of previous time-resolved measurements of electron properties is given in Sec. 2. In Sec. 3, the experimental set-up is described and the time-resolved measurement technique is introduced. Sec. 4 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. Finally, a conclusion is given in Sec. 5.

2 Review of previous works

Before describing the method to perform time-resolved measurements in a harmonic, low-frequency oscillation regime, it is worth briefly reviewing works carried out on this topic during the past few years.

Albarede et al. carried out time-resolved measurements in the near-field plume of a SPT-100 thruster using a single, cylindrical Langmuir probe based on a coaxial cable architecture [13]. The discharge current oscillations were acquired with a 50 MHz bandwidth current probe and the probe current was measured over a 1 kΩ resistor. The time evolution of the probe current was recorded for different bias voltages to reconstruct the current-voltage characteristic with a time resolution of 1 μs. The discharge current signal was used as trigger to synchronize the probe current waveform acquisition. The total acquisition duration to obtain the time-dependent current-voltage characteristic exceeded several minutes. The thruster discharge had to be identical for every single measurement in order to obtain a coherent dataset. The low-frequency oscillations in a Hall effect thruster are however non-stationary. Therefore identical events had to be selected for the triggering. Furthermore, these events had to represent the average behavior of the thruster. The trigger level was thus set 10 % higher than the mean discharge current. The recorded probe signal was averaged over 128 samples. By analysing the I-V characteristic at every time step using the classical theory of electric probes, the time-evolution of the plasma parameters (V_f, V_p, T_e and n_e) was obtained. The drawback of this method is that even if the trigger level is set to 10 % above the mean discharge current, the frequency content of selected events is not necessarily identical and hence the discharge behavior may be different for the different measurement points.

A different method of measuring transient plume properties was presented by Lobbia and Gallimore [14]. They used a high-speed Langmuir probe system to measure time series of current-voltage characteristics at every grid point in the plume. The sweep frequency was 100 kHz and the time resolution 10 μs. A null probe was used to correct for leackage currents due to the fast voltage sweep. The discharge current signal was sampled simultaneously with the probe characteristics. The time evolution of the plasma parameters (V_f, V_p, T_e and n_e) was obtained by means of the standard thin sheath theory. The obtained signals of the plasma parameters were then moved to the frequency domain by a fast Fourier transform. An average transfer function between the plasma parameter spectrum and the discharge current spectrum was determined for every grid point to create a statistically accurate model of the thruster-plume system. Time-coherent signals of the plasma parameters at every grid point were finally synthesized by using one common input signal of the discharge current. This approach has several disadvantages: First, the system is very complex, especially the electronic devices have to be designed to operate with such a high frequency. Second, only a low number of voltage steps is used to construct the current-voltage characteristic, which introduces an uncertainty in the measurement of the floating and the plasma potential [17]. Third, the model is solely correct if the frequency response and the power spectral density of the discharge current signal, used for the determination of the time-coherent plasma parameter signals, is similar to the initial signal, used to construct the transfer function.

Smith and Capelli presented a method to measure time and space-correlated plasma properties in the near-field using an emissive probe [15]. The discharge current and the probe potential, for the cold as well as for the heated probe, were recorded simultaneously to reconstruct the time correlated plasma properties (V_f, V_p and T_e) by synchronizing the temporal data to the dominant low-frequency discharge current oscillations. The electron temperature was obtained by an adequate model of the collected ion and electron currents. One of the drawbacks of this approach is that only an emissive probe is used. Hence, the electron density cannot be determined and the plasma potential as well as the electron temperature may be underestimated due to the high plasma electron temperature compared to the temperature of the emitted electrons [18]. Furthermore, this method does not provide an absolute determination of the temporal behavior for two reasons: First, the discharge properties are not identical from one low-frequency oscillation period to the next. Second, the determination of the dominant low-frequency oscillation is not absolute given the many higher frequency oscillations present in the signal.

3 Experimental set-up

3.1 Hall thruster

A 200 W Hall effect thruster with permanent magnets was used as an ion source. The thruster was operated at a discharge voltage of 225 V and an anode mass flow rate of 1.0 mg/s resulting in a mean discharge current of 0.92 A. The discharge channel walls were made of alumina. The thruster was operated in a 1.8 m in length and 0.8 m in diameter ground-test facility at a background pressure of 3×10^{-5} mbar.

3.2 Probes

A single cylindrical Langmuir probe was used to determine the plasma potential, the electron temperature and the electron density. The ALP system from Impedans was used to sweep the probe voltage and to measure the resulting probe current. The plasma potential was also assessed using an emissive probe heated with a current of 4.3 A. A detailed description of probes and data analysis was presented in a previous paper [19]. The two types of probes were fixed next to each other in the far-field plume of the thruster. The magnetic field strength at the probe location is about 1 G and the plasma can therefore be considered as magnetic field free. The probes were oriented parallel to the thruster axis. An examination of the discharge current evolution with and without the probes revealed that the probes do not influence the discharge behavior.

3.3 Time-resolved measurements

In order to perform proper time-resolved measurements, the thruster needs to be maintained in a periodic quasi-harmonic oscillation regime. This has two main advantages: First, the harmonic signal can be used as trigger signal, hence no need for a fast power switch that perturbates the thruster behavior [12]. Second, the thruster behavior is stationary. The frequency content is therefore the same at any time, which warrants reproducible measurement conditions. Furthermore time series can be added up without propagating noise and error.

To achieve a periodic quasi-harmonic operating regime of the thruster, a sinusoidal potential with a tunable frequency is applied between a floating electrode, here the keeper electrode, and the negative pole of the cathode heating circuit. A schematic view of the electrical set-up is represented in Fig. 1. The modulation frequency cannot be chosen randomly, is has to be one of the resonance frequencies of the discharge. 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 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 it does not represent significant perturbation.

The ALP system provides a time-resolved option. In this mode the probe current is recorded over one period of the modulation 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 this work, the time resolution was set to 1 μs and acquisition was averaged over 1000 records.

The time evolution of the potential of the cold and the heated emissive probe was recorded simultaneously to the discharge current oscillations. The power supply for the probe heating was powered via an uninterruptible power supply or an isolation transformer 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 bandwith of this configuration was about 60 kHz.

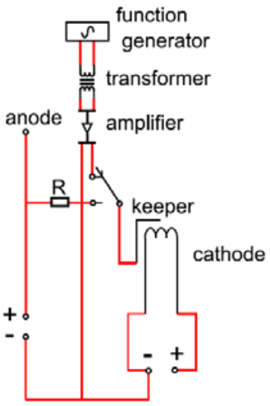

Fig. 1 Schematic view of the electrical set-up of the keeper electrode modulation.

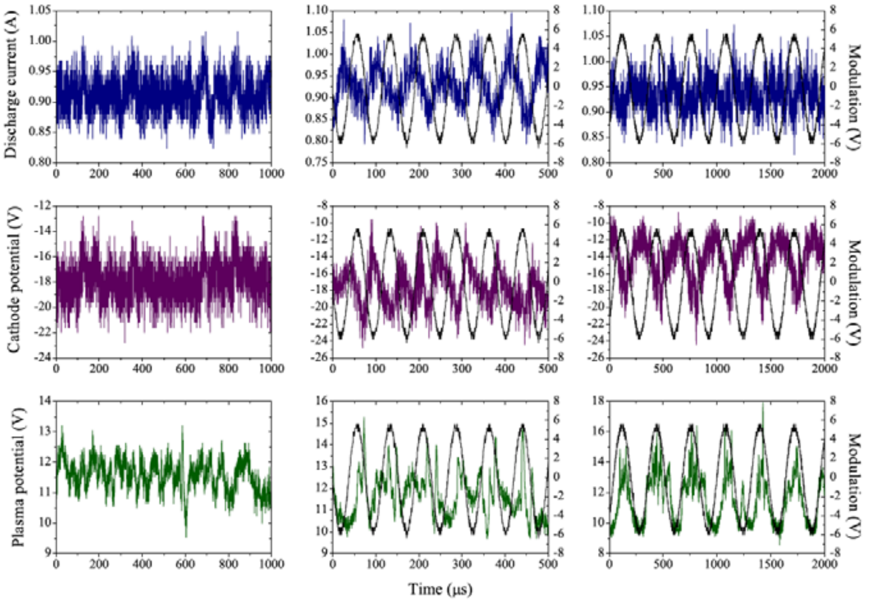

Fig. 2 Time series of discharge current I_d (first row), cathode-to-ground potential CRP (second row) and plasma potential V_p measured with a heated emissive probe at x = 200 mm and y = 0 mm (third row). First column column represents the time evolution of I_d, CRP and V_p without modulation, second colum for a modulation at 13.1 kHz and third column for a modulation frequency of 3.1 kHz. The displayed modulation (black line) is the signal from the function generator prior to amplification.

4 Results

4.1 Influence of the keeper voltage modulation on the discharge behavior

As has been mentioned before, in order to perform proper time-resolved measurements, the thruster discharge needs to be in a harmonic regime. Fig. 2 represents the time evolution of the discharge current I_d, the cathode-to-ground potential CRP and the plasma potential V_p as a function of the modulation frequency. The plasma potential is measured with a heated emissive probe at 200 mm downstream the thruster exit plane (x = 200 mm) on the thruster axis (y = 0 mm). As can be seen in Fig. 2, without a modulation signal, the discharge current 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 oscillation 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. In any case, the influence of the modulation on the mean discharge current is very weak ($\bar{I}_d = 0.92 \pm 0.01$ A). The time evolution of the cathode potential to ground is represented in the second row of Fig. 2. The CRP is well synchronized to the modulation at 3.1 kHz, at 13.1 kHz the synchronization is slightly worse, but still fairly good. Contrary to the discharge current, the mean value of the cathode potential is slightly different for the three operating conditions ($C\bar{R}P = 16.6 \pm 2.11$ V). The third row of Fig. 2 shows the behavior for the plasma potential. 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. Again the influence of the modulation on the mean value of the plasma potential is very weak ($\bar{V_p} = 11.64 \pm 0.18\,\mathrm{V}$).

4.2 Time-resolved measurements of plasma parameters

The time evolution of V_p, T_e and n_e for the two different modulation frequencies is displayed in Fig. 3 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 taken at 150 mm downstream the thruster exit plane and 25 mm off the thruster axis.

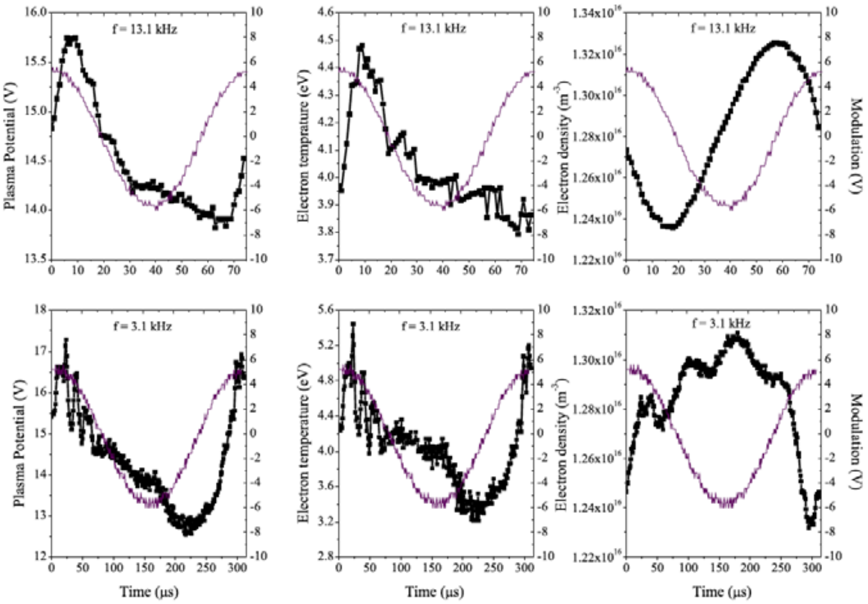

Fig. 3 Time evolution of plasma potential V_p, electron temperature T_e and electron density n_e measured with a Langmuir probe at x = 150 mm and y = 25 mm in the plume of the thruster operating at U_d = 225 V and D_a = 1.0 mg/s. The frequency of the keeper voltage modulation is 13.1 kHz, respectively 3.1 kHz. The displayed modulation (purple line) is the signal from the function generator prior to amplification.

As can be seen in Fig. 3, 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 changes 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 reproducible 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 54 % against 17 % for the electron temperature. The mean values of V_p, T_e and n_e do not depend significantly on the two modulation frequencies, in contrast to their different time evolution.

The time evolution of V_p, T_e and n_e is similar at different positions in the far-field plume [20]. Furthermore, the time evolution of the plasma potential measured by means of a Langmuir and an emissive probe are in fairly good agreement.

5 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. The plasma potential is also measured with an emissive probe. In order to perform 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.

Although the thruster is forced to a specific operating regime (harmonic oscillation), neither the global thruster behavior nor the mean value of the plasma parameters are significantly influenced by the modulation. The presented method is thus a powerful technique for performing proper time-resolved measurements of the plasma parameters in an instationary cross-field discharge. Further studies are necessary to test the technique for different operating conditions and with different Hall effect thrusters.

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