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# Compact high-speed reciprocating probe system for measurements in a Hall thruster discharge and plume

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A compact high-speed reciprocating probe system has been developed in order to perform measurements of the plasma parameters by means of electrostatic probes in the discharge and the plume of a Hall thruster. The system is based on a piezoelectric linear drive that can achieve a speed of up to 350 mm/s over a travel range of 90 mm. Due to the high velocity of the linear drive the probe can be rapidly moved in and out the measurement region in order to minimize perturbation of the thruster discharge due to sputtering of probe material. To demonstrate the impact of the new system, a heated emissive probe, installed on the high-speed translation stage, was used to measure the plasma potential and the electron temperature in the near-field plume of a low power Hall thruster. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4769052]

## I. INTRODUCTION

Electric propulsion is at present a well established technology for space applications.[1] In comparison with chemical rockets, electric propulsion devices offer an attractive way to save propellant mass, thanks to a very fast propellant ejection speed. Among all electric propulsion devices, Hall thrusters are currently recognized as an attractive propulsion means for long duration missions and maneuvers that require a large velocity increments. They are mostly used for geosynchronous satellite attitude control and station keeping. Besides, the ongoing development of high power Hall thrusters opens up the way to new applications such as orbit transfer, deorbiting maneuvers as well as deep space journeys.[2]

A Hall thruster is a gridless ion engine in a cross-field discharge. 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.[3,4] 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 solenoids 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.

In order to improve the performance level of Hall thrusters it is necessary to better understand the ionization and acceleration processes. Therefore, accurate measurements of the electron parameters in the near-field plume, which is typically the region between the thruster exit plane and the cathode plane, and even inside the discharge channel are essential. Electrostatic probes are a simple and versatile diagnostic tool for the experimental investigation of plasma properties.[5]

The plasma density inside the discharge channel and in the near-field plume is relatively large and the plasma is composed of highly energetic charged particles. This leads to sputtering and/or ablation of probe material by direct particle flux. The local plasma parameters, i.e., temperature and density, around the probe are then modified by the sputtered or ablated cold probe material. These modifications may remain localized near the probe, but they might also propagate further into the plasma and therefore influence the macroscopic plasma parameters, e.g., the discharge current and the cathode-to-ground potential.[6] The probe lifetime may also become an issue if it is inserted too long into the plasma. Considering all this, a high-speed reciprocating probe system is necessary to perform proper probe measurements inside the discharge channel and in the near-field plume of a Hall thruster.

Fast reciprocating probe systems have been extensively used to investigate edge effects in tokamaks.[7,8] These systems are based on external, pneumatic cylinders which provide drive speeds of several m/s. On the contrary, to investigate Hall thrusters, the high-speed actuator has to be placed inside the vacuum chamber as the thruster needs to be positioned as far as possible from the chamber walls in order to minimize interactions between the plasma beam and the chamber walls. Therefore, pneumatic systems cannot be used. A fast reciprocating system (High-speed Axial Reciprocating probe HARP) based on a linear electromagnetic motor assembly has been developed by the team of Professor Gallimore at the University of Michigan to study the plasma of a Hall thruster.[6] The HARP system can achieve a speed up to 3 m/s with a positioning resolution of 5 $\mu$m. However, this system is quite bulky and heavy and is thus not very flexible.

In the present paper a novel, compact high-speed reciprocating probe system based on a piezoelectric linear drive

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is presented. The advantage of such a system is that it is highly versatile due to its compact size and low weight. A first validation of the system was carried out with a 200 W Hall thruster. The spatial distribution of the plasma potential and the electron temperature was measured in the near-field plume by means of a cold and a heated emissive probe.

## II. EXPERIMENTAL SETUP

### A. NExET test bench

All experiments were performed in the NExET (New Experiments on Electric Thrusters) test bench. This vacuum chamber has been installed at the ICARE Laboratory in 2008. The stainless-steel vacuum chamber is 1.8 m long and 0.8 m in diameter. It is equipped with a multistage pumping system. This system is composed of a large dry pump (400 $m^3$/h), a 200 l/s turbomolecular pump to evacuate light gases and a cryogenic pump with a typical surface temperature of 35 K (8000 l/s) to get rid of the propellant such as xenon and krypton. A background pressure of $2 \times 10^{-5}$ mbar is achieved with a xenon mass flow rate of 1.0 mg/s and an input power of 250 W.[9] The back part of the chamber is water cooled and protected with graphite tiles to absorb a part of the ion beam energy and therefore reducing the thermal load onto the cryosurface. The chamber is equipped with different observation windows, diagnostic ports as well as electrical and gas feed-throughs. The interior of the test bench is easy to access, thanks to a large front door. The thruster was mounted onto a linear moving stage to allow a displacement in the axial direction.

### B. PPI thruster

The PPI thruster (French acronym for “Petit Propulseur Innovant”) was used for the experiments. This thruster is a 200 W type Hall thruster able to deliver a thrust of 10 mN when operated at 250 V and 1.0 mg/s xenon mass flow rate.[10] This thruster was originally designed by the GEMaC team in Versailles.[11,12] This thruster exhibits three interesting features that make it highly versatile.[13] First, the magnetic field is generated by way of small SmCo magnets brought together inside rings located on either side of the channel walls. A soft iron magnetic circuit with a back gap permits to drive the magnetic flux in order to obtain the desired topology. No magnetic screen is used. Second, the propellant gas is injected homogeneously inside the channel using a porous ceramic instead of a classical metal hollow gas injector. A stainless-steel ring placed at the back of the channel serves as anode. Third, a central copper heat drain is employed to evacuate heat towards a radiator placed behind the thruster. The radiator, which is a thin copper disk of 25 cm in diameter, is necessary to reduce the thermal load onto dielectric walls and magnets. The channel walls are made of alumina compound ($Al_2O_3$). A heated hollow cathode with a $LaB_6$ insert is used with a cathode mass flow rate of 0.2 mg/s.

### C. High-speed reciprocating probe system

In order to perform measurements of the plasma parameters in the near-field plume of a Hall thruster operated in a relatively small vacuum chamber, a compact but nonetheless fast-moving stage is necessary. The selected linear drive is a PILine® Linear Motor Stage M664K018. It is an ultrasonic piezo linear drive that does not use leadscrews or gearheads. It is backlash-free and does not create nor is it influenced by magnetic fields. The linear stage is very compact: the external dimensions are 140 × 63 × 14 mm. The total mass of the linear drive is solely 320 g. A picture of the piezo linear drive is shown in Fig. 1. The drive is composed of a stator that contains the piezoceramic oscillator and a slider (friction bar) that is attached to the moving part of the stage. The linear stage has a travel range of 90 mm with a speed of up to 350 mm/s and a resolution of 0.1 $\mu$m. Furthermore, it is vacuum compatible down to $10^{-6}$ mbar and has a lifetime of up to 20 000 h. The linear stage is controlled by a C-867 PILine® controller. This controller is a highly specialized proportional-integral-derivative (PID) servo-controller that is designed for closed-loop positioning systems equipped with PILine® piezo linear motion drives.

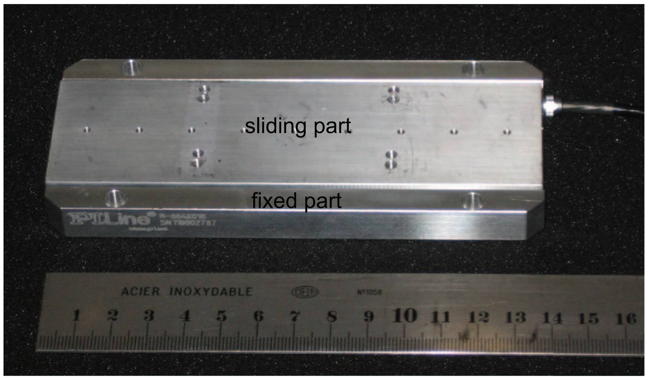

FIG. 1. Picture of the ultrasonic piezo PILine® Linear Motor Stage M664K018. The sliding and the fixed part of the linear drive are marked.

For the measurements of the plasma parameters in the near-field plume, an electrostatic probe (Langmuir or emissive probe) is mounted onto the piezo linear drive that is placed outside the thruster plume. The linear drive is placed under a graphite cover in order to protect it against direct ion bombardment and to prevent the motor to be extensively heated which would lead to a performance degradation. The probe is quickly moved to the measurement position. The controller of the piezo linear drive sends a trigger signal when the desired position is attained to start the probe measurement. After the measurement the probe is rapidly moved out of the near-field plume. In order to minimize the perturbation of the plasma due to the sputtered probe material, the residence time of the probe in the near-field plume should be as short as possible. A typical motion profile for a near-field measurement is shown in Fig. 2.

## III. EXPERIMENTAL VALIDATION

A first validation of the fast-moving probe system has been performed in the near-field plume of the PPI thruster in the $2S_0$ configuration[13] inside the NExET test bench. The thruster was operated at a discharge voltage of 200 V and an anode mass flow rate of 1.0 mg/s (xenon). A heated

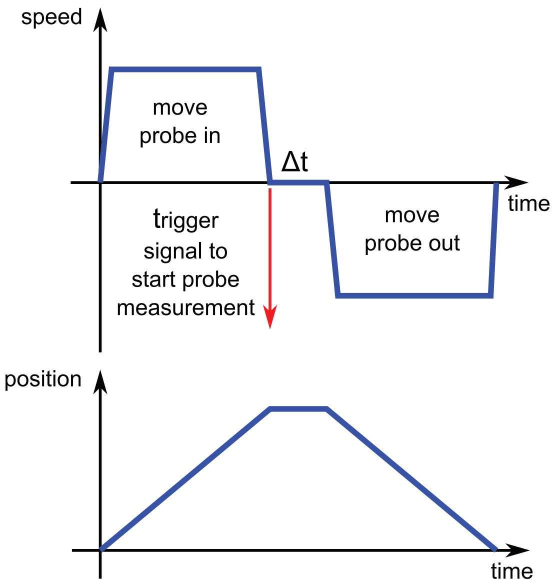

FIG. 2. Motion profile of the fast reciprocating probe for the measurement of $V_p$ in the near-field plume.

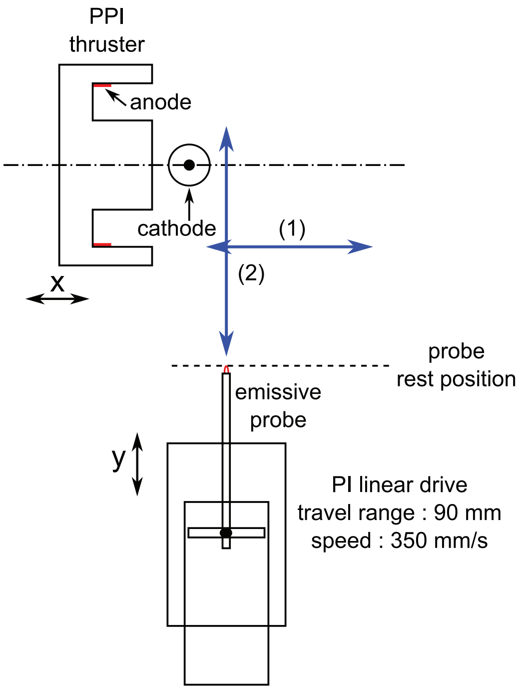

FIG. 3. Schematic view of the setup (not at scale). The blue arrows show the implementations of the first and second measurement series.

emissive probe was used as it provides an instantaneous measurement of the plasma potential.[14] The probe was built of a 8 mm long loop of 150 $\mu$m in diameter thoriated tungsten wire. The plasma potential is assumed to be the floating potential of the emissive probe heated with a current of 4.3 A. A more detailed description of the probe and the analysis is given in a previous paper.[5] An estimation of the electron temperature can also be obtained from emissive probe measurements. The electron temperature can be determined from the floating potential of the cold and the heated emissive probe based on the knowledge of the collected ion and electron currents at a given potential. Therefore, the floating potential of the cold ($\phi_{fl}^{cold}$) and the heated emissive probe needs to be recorded. The electron temperature can then be calculated using the following equation:[15]

$$T_e = \frac{\phi_{fl}^{cold} - V_p}{4.27}. \tag{1}$$

The denominator of the above mentioned equation depends in fact on the difference between the "true" plasma potential and the floating potential of the heated emissive probe.[15] Furthermore, this method requires a Maxwellian electron energy distribution function (EEDF). The uncertainty in the denominator of Eq. (1) and a possible deviation from a Maxwellian EEDF may decrease the accuracy of the presented electron temperature measurement. The fast-moving system is positioned next to the thruster so that the emissive probe can be moved into the near-field plume perpendicular to the thruster axis. The thruster is placed on a linear motion table so that measurements can be taken at different axial positions downstream the thruster exit plane. A schematic view of the setup is shown in Fig. 3.

As a first step of the system validation it was checked that the probe does not perturbate the discharge behavior. Therefore, the discharge current was recorded while moving the probe into the near-field plasma plume and out at a distance of 20 mm downstream the thruster exit plane. The probe was moved up to 5 mm ahead the channel centerline (this radial position actually corresponds to the outer channel wall), stopped there for 10 ms and then moved back to the rest position. The plasma potential measured by the emissive probe was recorded simultaneously to the discharge current. The time evolution of $I_d$ and $V_p$ during the probe sweep is shown in Fig. 4. As can be seen, $V_p$ increases when moving the probe in and decreases when moving the probe out. Moreover, the profile of $V_p$ is perfectly symmetric, as expected if the probe has no impact on the plasma parameters. Furthermore, no influence of the probe position on the discharge current is visible. One can therefore assume that the discharge behavior as well as the plasma parameters are not perturbated by the fast-

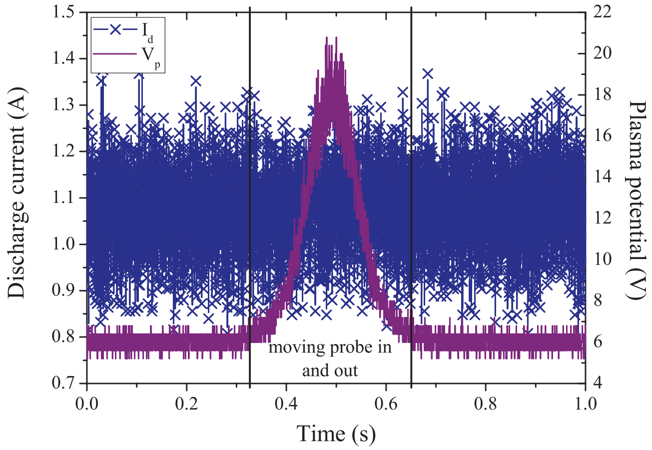

FIG. 4. Discharge current and plasma potential time series measured by means of a current probe and a heated emissive probe during probe sweep.

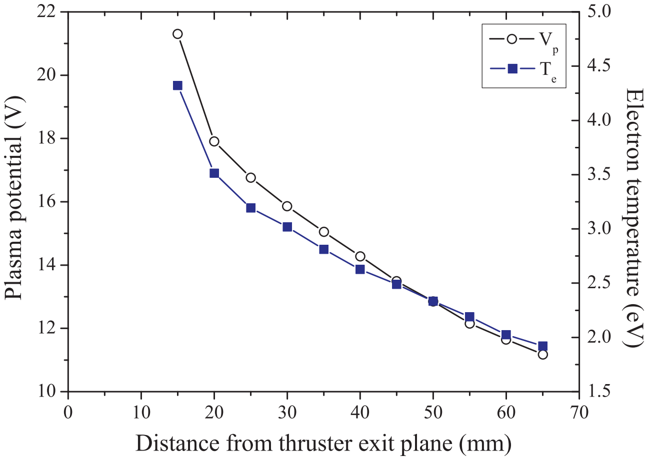

FIG. 5. Axial profile of $V_p$ and $T_e$ measured with the emissive probe in the near-field plume along axial direction 5 mm away from the channel centerline of the PPI thruster operating at 200 V and 1.0 mg/s.

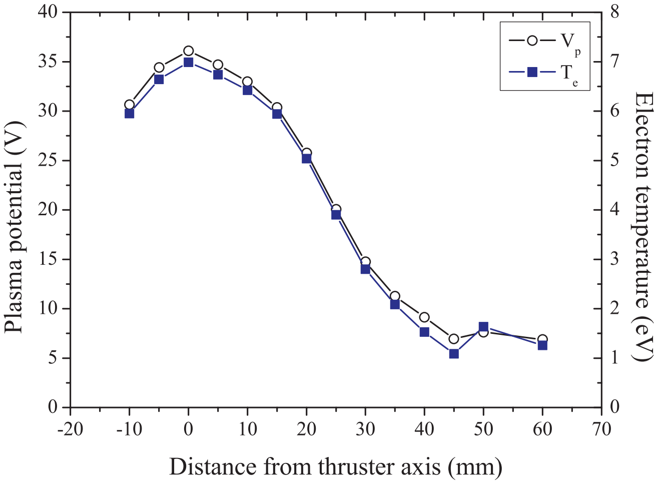

FIG. 6. Radial profile of $V_p$ and $T_e$ measured with the emissive probe in the near-field plume 20 mm downstream the channel exit plane of the PPI thruster operating at 200 V and 1.0 mg/s.

moving probe system during near-field plume measurements. Various stop periods up to 1 s have been tested and no influence of the probe insertion on the discharge current as well as on the plasma potential was noticed.

The next step of the system validation consisted in measuring the plasma potential and the electron temperature at different positions in the near-field plume of the PPI thruster. Therefore, the cold or the heated emissive probe was moved into the near-field plume and the measurement of the probe potential was initiated by the trigger signal of the piezo linear controller once the probe has attained its position. Two series of measurement have been carried out: First, $V_p$ and $T_e$ were measured as a function of the axial distance $x$ from the thruster exit plane $x$ 5 mm away from the channel centerline from 15 to 65 mm downstream the thruster exit plane by steps of 5 mm. The results are shown in Fig. 5. As can be seen, $V_p$ and $T_e$ decreases with an increasing $x$. This can be explained by the fact the plasma plume of a Hall thruster is an expansion in a supersonic regime.[5,16]

Second, $V_p$ and $T_e$ were measured as a function of the distance from the thruster axis $y$ at a distance of 20 mm downstream the thruster exit plane. Measurements were performed every 5 mm from −10 to 60 mm away from the thruster axis. The evolution of $V_p$ and $T_e$ as a function of $y$ is represented in Fig. 6. As can be seen, the plasma potential as well as the electron temperature are maximum on the thruster axis and they decrease with an increasing $y$. This can again be explained by the expansion of the plasma plume.

Note that the plasma potential measured by the emissive probe is certainly underestimated as the electron temperature in the plasma near-field plume is much higher than the temperature of the electrons emitted by the emissive probe.[5] In order to get a more accurate estimation of $V_p$ and $T_e$, a Langmuir probe should be used. In addition, a Langmuir probe would provide a measurement of the electron density and the electron energy distribution function. However, using a Langmuir probe in the near-field plume is less straightforward. First, a voltage sweep of the probe is necessary in order to obtain the current–voltage characteristic. Second, in the area close to the thruster exit plane the magnetic field is not negligible and one needs therefore to account for it for the Langmuir probe $I$–$V$ curve analysis. An emissive probe is less sensitive to magnetic fields.[14]

It is also interesting to notice that as the probe residence time in the high density plasma region is only very short, the probe lifetime is not an issue. Several hours of measurements have been performed with the same probe during the testing.

## IV. CONCLUSION

A new, compact high-speed reciprocating probe system has been developed. This system is based on an ultrasonic piezo linear drive with travel range of 90 mm and a speed of up to 350 mm/s.

A first validation of the new system was performed in the near-field plume of a low-power permanent magnet Hall thruster. It has been demonstrated that the discharge behavior of the thruster is not influenced by the probe insertion up to a residence time of 1 s in the plasma plume. The plasma potential and the electron temperature were measured by means of a cold and a heated emissive probe at different positions in the near-field plume of the PPI thruster operating at 200 V and 1.0 mg/s of xenon. The plasma potential and the electron temperature are maximum on the thruster axis and decrease with the distance from the thruster exit plane and the thruster axis due to the fact that the plasma plume is an expanding plasma jet in a supersonic regime.

The compact high-speed reciprocating probe system can now be used for a detailed investigation of the discharge and the plume at different operating conditions of various Hall thrusters. It would be better to use a Langmuir probe instead of an emissive probe in order to get more accurate measurements of the plasma potential and the electron temperature and to be able to determine the electron density and the electron energy distribution function.

In a more general way, this device can be used with other plasma thrusters and with other low-pressure plasma sources for which diagnostic tool lifetime or impact of the probe insertion on the plasma parameters are an issue. The device is easy to implement in a test bench. It is also compatible with vacuum chambers equipped with a lock chamber as it can be mounted onto the thruster/source assembly thanks to its compact design and low weight. This is profitable as one does not need to enter/open the vacuum tank for alignment or probe repairing.

## ACKNOWLEDGMENTS

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