E×B probe investigation of the PEGASES thruster ion beam in Xe and SF_6

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Abstract: The ion velocity distribution function has been measured in the unconventional PEGASES ion thruster with an E×B probe for several conditions and two propellant gases, namely Xe and SF_6. The PEGASES thruster has been operated as a classical ion thruster with xenon as propellent where positive ions are accelerated. The measurements of the E×B probe are used to show the velocity of the ions inside the plume of the thruster. The measurements show also that the E×B probe can be used to identify different ion species in the plasma as well as multiply-charged ions. In addition, first measurements of the E×B probe in the PEGASES thruster with SF_6 as propellant are reported. The use of SF_6 leads to the formation of a strongly electronegative plasma inside the thruster chamber. The acquired E×B spectra demonstrate that both positive and negative ions can be identified and their respective fractions can be assessed.

Nomenclature

B = magnetic field
E = electric field
F_L = Lorenz force
M = ion mass
V_b = grid bias potential
V_p = plasma potential
v_i = ion velocity
Z = ion charge number

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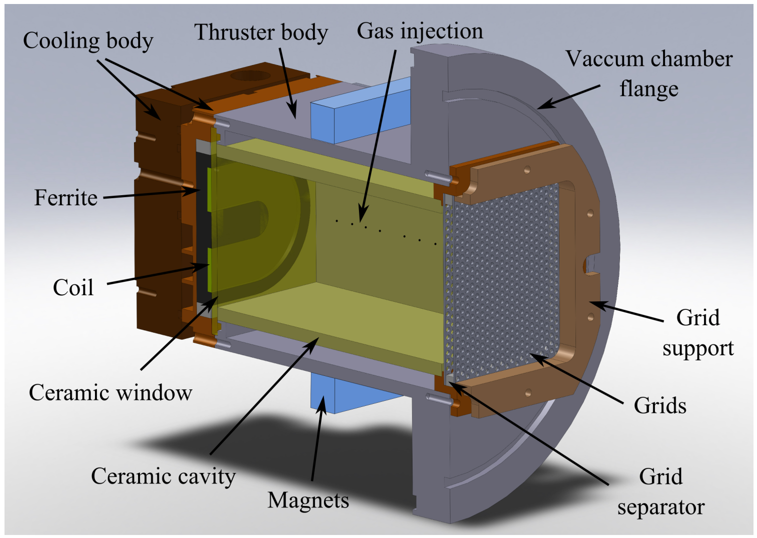


Figure 1. CAD Model of the PEGASES thruster prototype.

I. Introduction

Ion engines and Hall thrusters currently operate with noble gases such as xenon. Xenon is a non-toxic gas with a relatively low ionization potential. When using a noble gas as propellant, it is of course necessary to neutralize the ion beam with an electron stream to cancel the space-charge limitation. A hollow cathode is often employed as an external neutralizer. Addition of a cathode together with its power supply, however increases the weight, the complexity and the risk of failure.

In 2007, researchers at the Laboratoire de Physique des Plasmas in France patented an innovative thruster concept: PEGASES for Plasma Propulsion with Electronegative GASES.[1] A drawing of the PEGASES thruster is shown in Fig 1. Instead of creating and accelerating only positive ions, PEGASES ejects pair of positive and negative ions. The current PEGASES thruster is a Radio-Frequency (RF) gridded ion engine operating with an electronegative gas such as sulfurhexafluoride (SF_6). Positive ions are formed by electron impacts on neutral molecules. Negative ions are formed through a dissociative attachment reaction. As the cross-section for dissociative attachment decreases with the electron temperature, production of a large amount of negative ions requires cold electrons. A magnetic filter is therefore used to slow down electrons and to cool them down through, among others, collision with neutrals.[2] Behind the magnetic filter region, the plasma is solely composed of pairs of positive and negative ions. This very peculiar state of matter is called an ion-ion plasma. The two ion species are subsequently electrostatically accelerated by means of polarized grids. The sign of the acceleration potential is alternately changed in order to extract the two types of ions. The advantage of the PEGASES thruster is that it doesn't require a neutralizer and the large recombination rate downstream the grid assembly warrants a low ionization degree in the beam. As a consequence, particle interaction with the spacecraft is strongly reduced. The PEGASES source is an inductively coupled discharge, which operates at 4 MHz. The RF power ranges between 80 W and 200 W. The PEGASES cavity is made with ceramic walls thereby the plasma is floating. Magnets are used to generate the transverse magnetic field of the filter. The acceleration stage is composed of two planar grids made out of stainless steel. The grids are 0.8 mm thick and spaced 1 mm apart with a hole size of 2 mm and a transparency of 60 %. The upstream screen grid is at high potential. The downstream acceleration grid is grounded. More details about the thruster are provided by the following sources.[3–5]

In this contribution we present results obtained with the PEGASES thruster operating with xenon and SF_6 as a propellant gas. The gist is to obtain and compare ion beam properties. Notice that, when fired with, a hot tungsten filament is used as an external neutralizer. The electrical schematics are shown in Fig. 2.

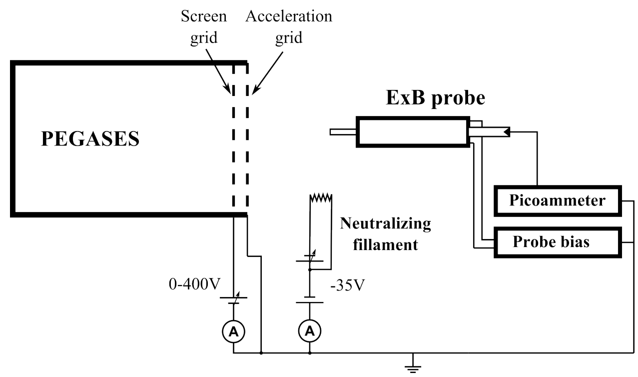


Figure 2. Electrical setup of the E×B probe experiment with the PEGASES thruster.

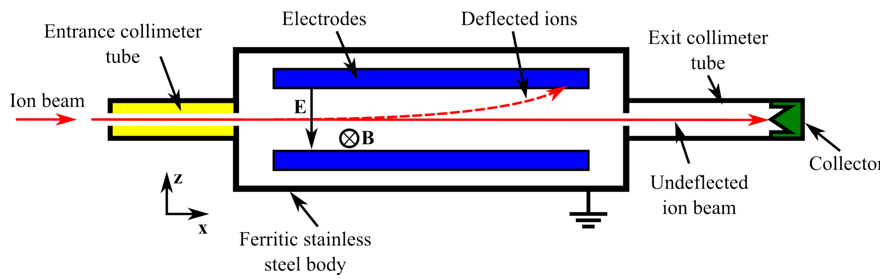


Figure 3. Schematic drawing of the E×B probe.

II. E×B Probe

An E×B probe, also called a Wien filter, is a diagnostic tool that allows to measure ion velocity in a given direction.[6] A schematic drawing of the E×B probe is presented in Fig. 3. The basic principle of the probe relies on drift in crossed electric and magnetic fields. The motion of singly charged ions in an electric and magnetic field is described by the Lorenz force F_L:

$$\mathbf{F}_L = e(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}), \tag{1}$$

where e is the elementary charge, $\mathbf{E}$ and $\mathbf{B}$ the electric and magnetic field, respectively, and $\mathbf{v}_i$ the ion velocity vector. The Wien filter discriminates particles with distinct velocity. When the particles undergo no force in a cross-field region, i.e. the Lorentz force is null, previous equation becomes,

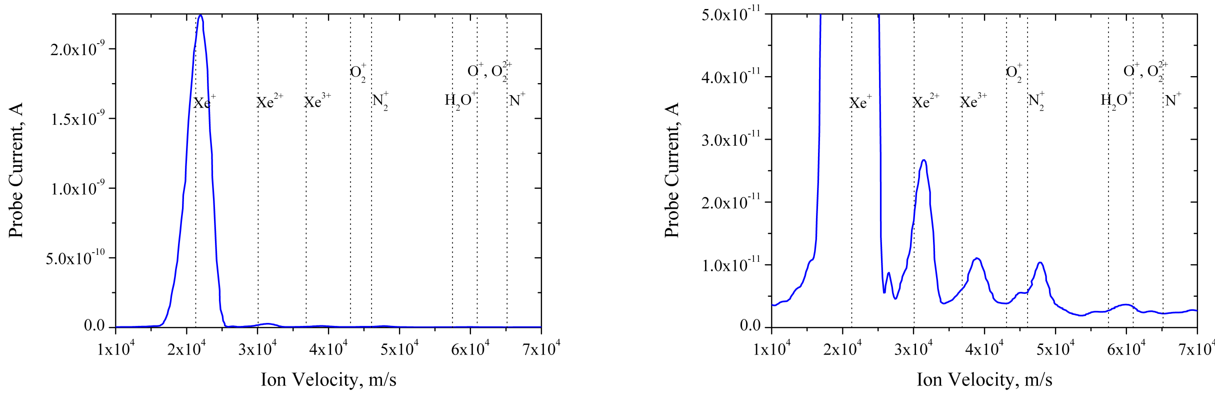
$$v_i = \frac{E_x}{B_y}. \tag{2}$$

A compact high-accuracy E×B probe has been developed at ICARE for diagnosing ion beams of electric thrusters.[7] The probe length is around 30 cm. The magnetic field is fixed inside the device. A magnetic circuit is used to make the field homogeneous and symmetrical. The electric field, which is perpendicular to $\mathbf{B}$, is tuned by varying the potential applied on two parallel electrodes. The ion collector current is accurately measure with a picoampermeter (accuracy $\sim$ 10 pA). Sweeping the electrode voltage allows to acquire the ion velocity distribution function.

III. E×B Probe Velocity Measurements

A. Measurements in Xenon

Measurements with an E×B probe have been performed to obtain the velocity distribution function (VDF) of the ions in the plume of the PEGASES thruster. The entrance of the probe has been placed 15 cm behind the grids on axis of the probe unless otherwise mentioned. Figure 4 shows an E×B spectrum in a



(a) (b)

Figure 4. Measurement with the E×B probe at 288 V acceleration grid bias in a 5 sccm xenon discharge at 100 W. The whole VDF is shown in (a) and (b) shows the same measurement where the first peak is cut of to better visualize the succeeding peaks.

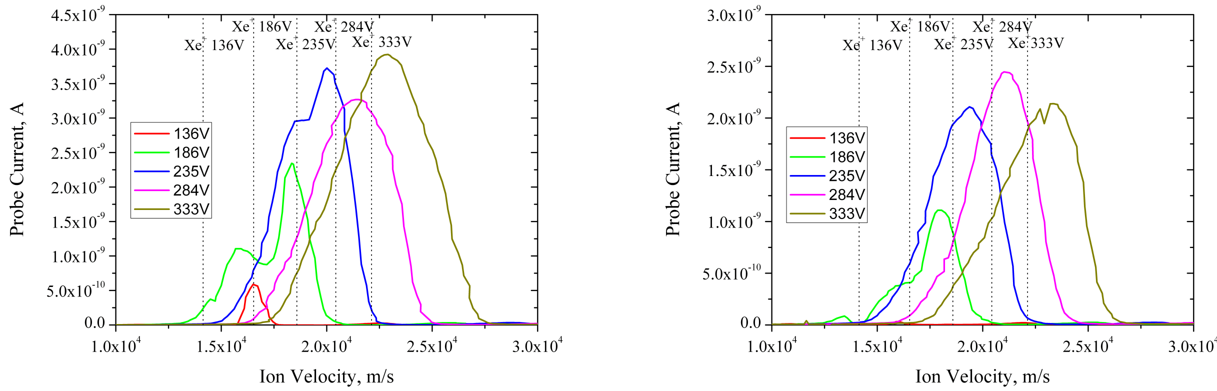
5 sccm, 100 W xenon discharge with an applied acceleration grid bias of 288 V. The dotted lines represent the expected velocities of the ion species which can be calculated with,

$$v_i = \sqrt{\frac{2Ze\left(V_b + V_p\right)}{M}}, \tag{3}$$

where Z is the ion charge number, V_b is the bias potential, V_p is the plasma potential and M is the ion mass.

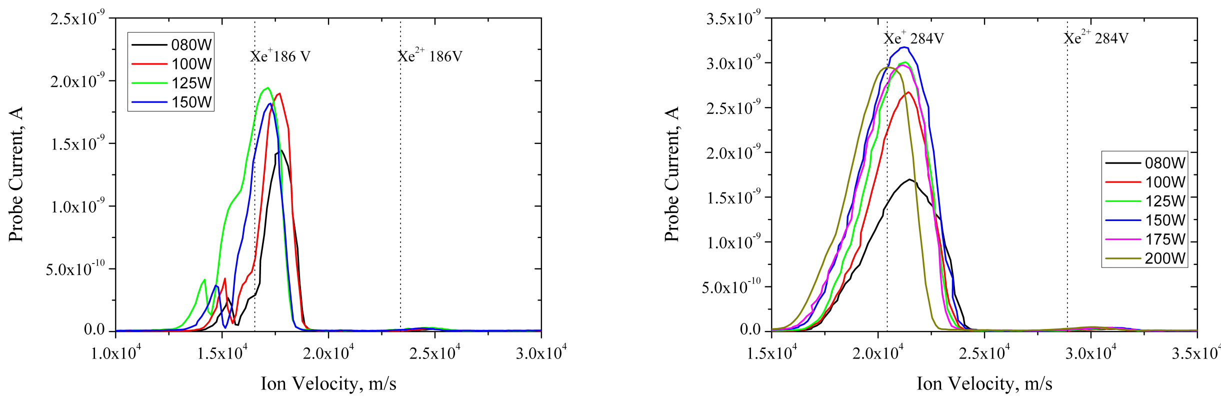
Measurements show that the ions velocity is usually above the speed calculated when using only the grid bias as accelerating potential. One possible source for the discrepancy is the plasma potential. This is why Eq. 3 contains a term for the plasma potential. The ions get accelerated between the plasma and the screen grid in the discharge chamber as the plasma is at a higher potential than the screen grid. Measurements with a Langmuir probe show a plasma potential of roughly 20 V for the discharge conditions shown in Fig. 4. Therefore the calculation of the expected velocities have been done with 308 V while the applied bias voltage was 288 V. The remaining observed discrepancies in velocities are most probable due to calibration errors with the E×B probe. Figure 4 shows peaks for Xe^+, Xe^{2+} and Xe^{3+} as expected. The Xe^{2+} ions account for 0.51 % and the Xe^{3+} for 0.17 % of the xenon ion amount. The numbers have been obtained by integrating the area under the peaks and set them into relation with the main peak. This is low compared to 11 % for Xe^{2+} and 1 % for Xe^{3+} obtained in a Hall thruster at a discharge voltage of 300 V.[8] Furthermore peaks which are most likely O_2^+ and N_2^+ can be observed. This is probably due to a small leak in the thruster or the gas feed line where air can enter into the discharge chamber. Due to observations of the pressure it can be estimated that the leak is a fraction of a sccm and will not change the measurements drastically. The expected velocities for H_2O^+, O^+, O_2^{2+} and N^+ have been marked in Fig. 4. Peaks in the measurements can be observed which might correspond to these ions but the noise level is to high to make certain claims. With a higher averaging and an improved signal strength these species could probably be better identified.

Measurements with the E×B probe have been performed over a wide range of parameters. Figure 5 shows the VDF for (a) 2.5 sccm and (b) 5 sccm for different acceleration grid biases at a input power of 100 W. The pressure inside the vacuum chamber was $3 \cdot 10^{-4}$ mbar-N$_2$ in the case of the 2.5 sccm flow rate and $7 \cdot 10^{-4}$ mbar-N$_2$ for the 5 sccm flow rate. As previously mentioned the measured velocities are usually a bit higher than the calculated velocities. The dotted lines are based on the screen grid bias in the following figures. The velocities follow the bias as expected and the signal strength increases with the bias. The lower limit of the measurements has been given by a low signal strength for grid biases of less than 136 V. The signal for the low biases of 136 V and 186 V show a strong discrepancy with the expected velocity. The signal strength for the biases of 235 V, 284 V and 333 V seem to be where a full acceleration of the ions is achieved and the signals resemble each other. The upper limit has been given by arcing between the grids. The arcing depends on different factors such as the pressure in the chamber and is favored by deposition of conducting metals on the grid separator.



(a) (b)

Figure 5. Velocity profile measured with an E×B probe for different acceleration voltages on the grid. The profiles were measured at 100 W input power and (a) 2.5 sccm and (b) 5 sccm flow rate



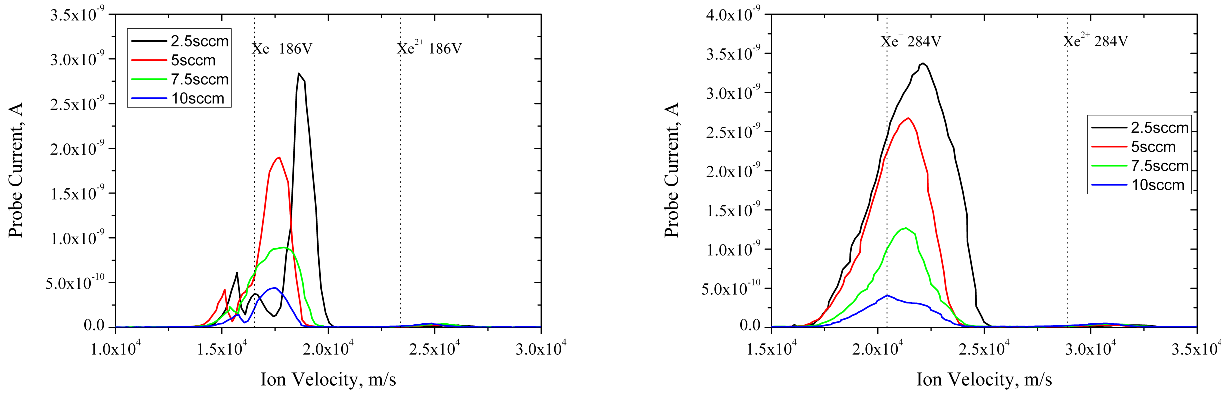
(a) (b)

Figure 6. Velocity profile measured with an E×B probe for several input power. The profiles were measured at a flow rate of 5 sccm and (a) 186 V and (b) 284 V grid bias

Figure 6 shows the VDF for several input powers for two grid biases, (a) 186 V and (b) 284 V at a pressure of $7 \cdot 10^{-4}$ mbar-N_2 at a 5 sccm flow rate. The measurements show for both acceleration voltages that the signal is lower for the 80 W power input. For the powers exceeding 100 W no clear difference is observable. In theory the measured ion current should increase with the power as the ionization degree and therefore the ion flux inside the cavity increases. This effect might lie hidden within the error margin of the probe as the variation in the signal is only around 15 % for the input powers above 100 W.

In order to investigate the influence of the pressure on the acceleration of the ions the E×B probe has been placed in the plume of the PEGASES thruster and the flow rate has been varied between 2.5 sccm and 10 sccm with the pressure ranging from $3 \cdot 10^{-4}$ mbar-N_2 and $1.5 \cdot 10^{-3}$ mbar-N_2. Figure 7 shows the VDF for a grid bias of (a) 186 V and (b) 284 V and an input power of 100 W. It can be seen that the signal strength increases with decreasing flow rates which is in accordance with planar probe measurements. A increase in the velocity can be observed for the lower flow rates, this is probably due to the fact that the plasma potential increases in these cases.

The E×B probe has been mounted on a rotary platform to investigate the angular dependency of the ions in the thruster plume. The rotation axis was orthogonal to the (x,y) plane. As the rotary platform could not be operated from outside the chamber the vacuum chamber had to be pressurized between the different



(a) (b)

Figure 7. Velocity profile measured with an E×B probe for several flow rates. The profiles were measured at 100 W input power and (a) 186 V and (b) 284 V grid bias

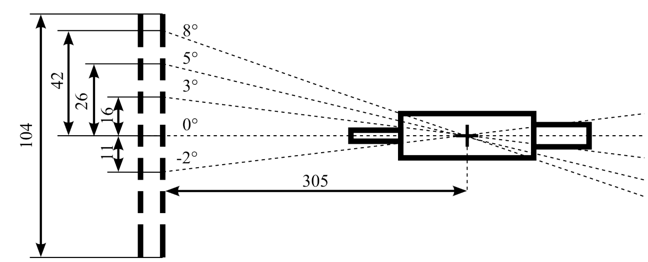


Figure 8. Schematic drawing of the angular measurements performed with the E×B probe.

angular measurements. This results in slightly different operating conditions for each measurement. The center of the E×B probe was located 305 mm away from the acceleration grids as in the previously presented experiments. Rotation around this point leads to the E×B probe pointing at different points on the grid. Figure 8 illustrates the experimental configuration.

The results of this experiment are presented in Fig. 9. The measurements have been performed with 100 W input power and 260 V screen grid bias for flow rates of 2.5 sccm with a pressure of $3 \cdot 10^{-4}$ mbar-N_2 and a 5 sccm flow rate with a pressure of $8 \cdot 10^{-4}$ mbar-N_2. The measurements show no strong dependency with the angle on the signal strength or the velocity. The measurement at 5° degree shows a slightly higher velocity and a higher signal. In the contrary, the measurement at 8° angle shows a reduced signal strength. The small observed changes follow no trend and might be due to the fact that the measurements had to be spread out over several days and the same plasma conditions are hard to reproduce. The results of the measurements lead to the assumption that the grid plane of the PEGASES thruster can be considered a uniform ion source with an divergence angle of at least 8°.

In order to evaluate the behavior of the PEGASES thruster and the E×B probe in different conditions experiments in argon have been performed. The ionization energy of argon is higher than the one for xenon (15.76 eV against 12.13 eV). Stable discharge conditions where only possible for an input power of 150 W. The pressure inside the vacuum chamber was $3 \cdot 10^{-4}$ mbar-N_2 for the 10 sccm flow rate and $2 \cdot 10^{-4}$ mbar-N_2 for the 5 sccm flow rate. The results of the measurement are presented in Fig. 10. The expected velocity is based on the acceleration bias of the screen grid as the plasma potential inside the cavity has not been measured for argon. It can be seen that the same behavior can be observed as in the measurements with xenon. The signal strength increases for the lower flow rates. The ion velocity is also higher in the case for the 5 sccm flow rate. Table 1 shows the velocity at the peak of the signal and a conversion of the velocity back to the acceleration voltage with Eq. 3. It can be seen that the applied acceleration bias and the theoretical acceleration voltage have a difference between 30 V and 56 V. This is quite large as being the sole result of the plasma potential. The calibration of the E×B probe probably factors in as well as possible alignment

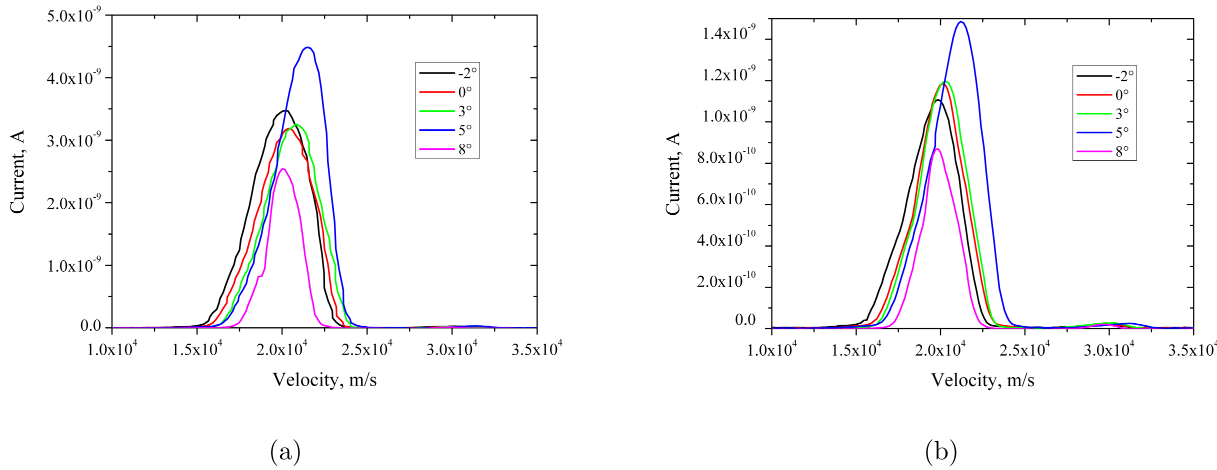


Figure 9. Velocity profile measured with an E×B probe for several angles. The profiles were measured at 100 W input power and 260 V grid bias with flow rates of (a) 2.5 sccm and (b) 5 sccm.

Accel. bias V_b, V	Flow rate, sccm	Ion velocity, m/s	Theor. accel. bias, V	Δv, V
175V	5	33418	231	56
175V	10	31438	205	30
275V	10	39050	316	-41

Table 1. Measured velocities with the E×B probe in a 150 W argon discharge and the theoretical acceleration bias.

problems. For the higher flow rates the difference is lower as expected as the plasma potential at higher flow rates are usually lower for the same conditions.

The E×B probe has been placed on a linear drive inside the vacuum chamber to investigate the plasma plume properties along the beam axis. The center of the E×B probe had a distance of 305 mm to the acceleration grid in all previous experiments. With the linear drive, the center of the probe can be displaced between 430 mm and 680 mm. The measurements have been conducted in a 5 sccm xenon plasma at a pressure of $7 \cdot 10^{-4}$ mbar-N_2 with an input power of 100 W and a grid bias of 160 V and 260 V. The measurements, presented in Fig. 11, show the main Xe^+ peak only when the probe is close to the grid for a screen grid bias of 160 V. A small peak shows up in the measurements. Its velocity slightly changes with increasing distances. This peak can also be seen in Fig. 5, Fig. 6 and Fig. 7 and has also been observed in Hall thrusters.[7,9] For the measurements with the 260 V bias we can see that the signal of the main xenon peak reduces with the distance. With increasing distance the single large peak develops into two peaks. The first peak resembles the small unexplained peek which also shows up in the other measurements. This peak seems to be hidden in the main peak when the signal strength is higher. The appearance of this small peak seems to be connected to the probe itself as it has been observed in the PEGASES thruster and two different Hall thrusters. Apart from this no further explanation can be provided until further investigations have been conducted. The effect that the signal decreases with the distance is due to a divergence of the beam and charge exchange.

B. Measurements in SF_6

The PEGASES thruster is normally operated in an electronegative plasma with a propellant gas like SF_6 to create negative and positive ions. In these experiments the magnetic filter has been used to increase the negative ion production in the thruster. The idea of the PEGASES thruster is to accelerated the positive and negative ions alternately by changing the grid bias with a high frequency. Measurements with the E×B probe require a long integration time to resolve the very low currents. As a consequence the measurements cannot be carried out with alternate acceleration.

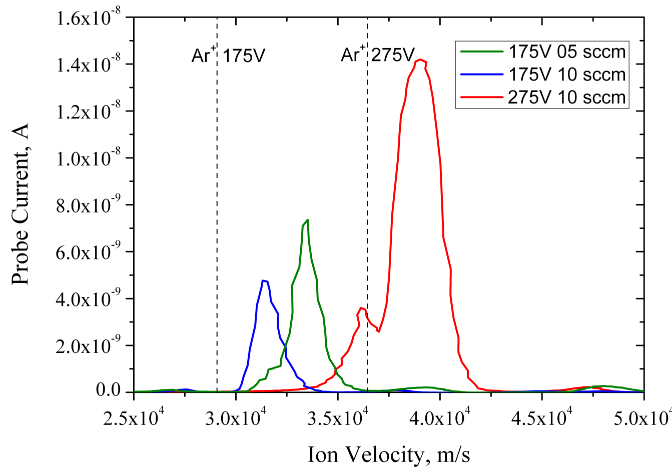
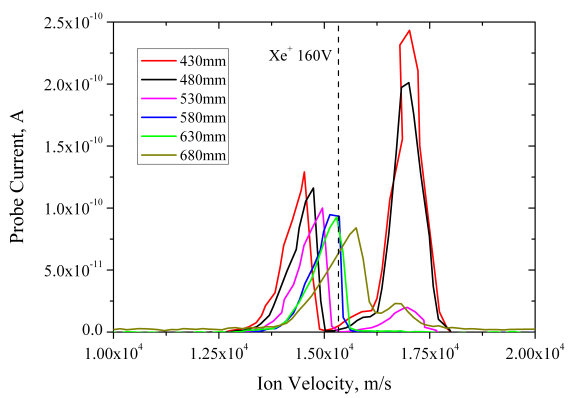
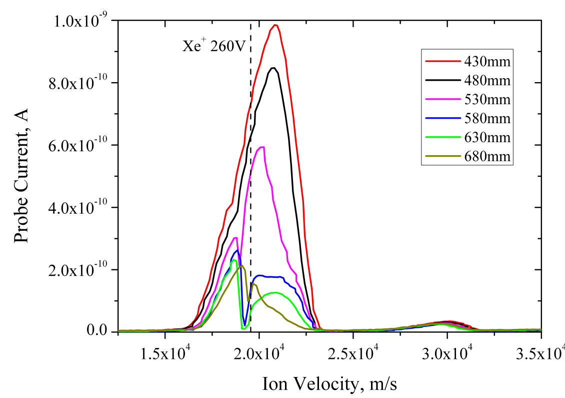


Figure 10. Measurements with the E×B probe in argon for different conditions.



(a)

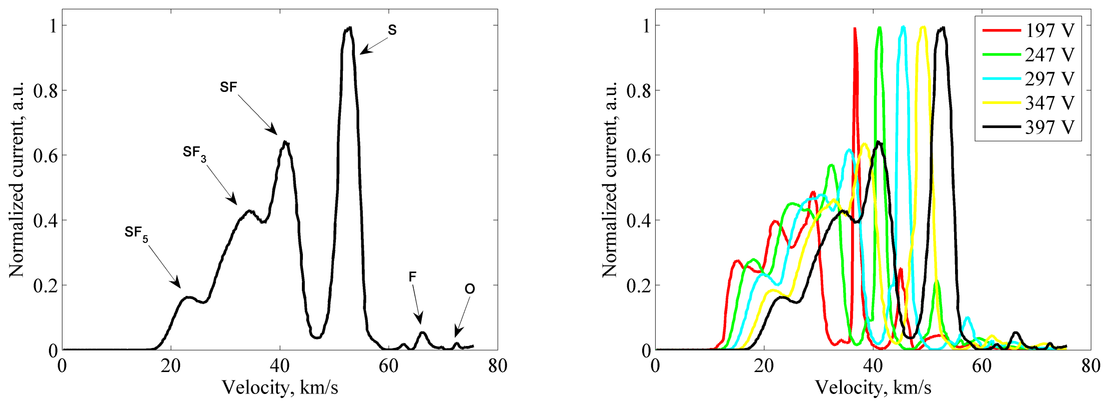


(b)

Figure 11. Velocity profile measured with an E×B probe for varying distances. The profiles were measured at 100 W input power and 5 sccm xenon flow rate for a grid bias of (a) 160 V and (b) 260 V.

	SF_6^+	SF_5^+	SF_4^+	SF_3^+	SF_2^+	SF^+	S^+	F^+	O_2^+	O^+	N_2^+	N^+
Atomic mass	146	127	108	89	70	51	32	19	32	16	28	14
v_i in km/s at 400 V	22.9	24.6	26.7	29.4	33.2	38.8	49.1	63.7	49.1	69.2	52.4	74.2

Table 2. The atomic mass for different ion species and their ion velocity at an acceleration voltage of 400 V.



(a) (b)

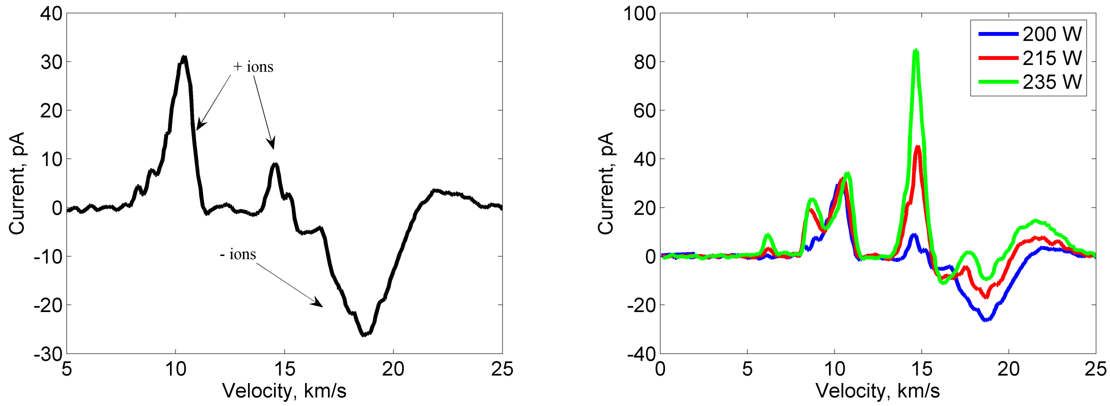
Figure 12. Velocity profile measured with an E×B probe in SF_6 and a magnetic field of 170 G. The profiles were measured at 200 W input power, 5 sccm SF_6 flow rate at a pressure of $3 \cdot 10^{-4}$ mbar-N_2 for a grid bias of (a) 400 V and (b) varying grid bias.

The measurements presented in Fig. 12 have been performed with a constant positive grid bias. That means only positive ions can be extracted and accelerated. The measurements have been conducted at 200 W input power, 5 sccm SF_6 flow rate at a pressure of $3 \cdot 10^{-4}$ mbar-N_2 for a grid bias of (a) 400 V and (b) varying grid bias. The magnetic field used in this experiment was 170 G. A hot filament is used as a neutralizer.

Six peaks can be clearly identified in the spectrum in Fig. 12 (a). They correspond to SF_5^+, SF_3^+, SF^+, S^+, F^+ and O^+ in the velocity range from 15 km/s to 65 km/s. The mass of the different SF_x ions species are close together which makes it sometimes difficult to identify their separate peaks in the signal. Tabel 2 shows the atomic mass of different ions species and their expected velocity for an acceleration voltage of 400 V. The signal for the SF_4^+ ions and the SF_2^+ ions are probably less strong and are hidden in the signal between the other peaks.[10] The difference between SF_5^+ and SF_4^+ is only 2 km/s at this acceleration voltage. The signal for the sulfur ions is stronger than for the other ion species. This is probably due to the fact that the ionization energy is low compared to the other species (10.36 eV for sulfur compared to 17.42 eV for fluorine). Figure 12 (b) shows the evolution of the E×B traces for acceleration voltage bias between 197 V and 397 V for the same conditions. The ion velocity follows the acceleration bias as one would expect.

While applying a positive extraction bias on the grids only positive ions get accelerated. The E×B probe was placed at the entrance of the PEGASES cavity with only one grid with a hole for the entrance collimator in the middle. This setup has been chosen in order to trace all ion species in the spectrum and ensure similar discharge conditions. This grid has not been biased. In this experiment the profiles were measured at 6 sccm SF_6 flow rate at a pressure of $3 \cdot 10^{-4}$ mbar-N_2 for various input powers at a magnetic field of 170 G. The acquired traces presented in Fig. 13 reveal positive and negative ion species. Note that the signal measured with the collector corresponds to the sum of the positive and negative ion beam contribution, i.e. the probe will show zero current if a positive and negative ion beam with the same content and strength reach the collector. Part (b) of the figure shows the evolution of the spectrum for an increasing input power. The signal peaks rises with the power which indicate an increased ion density. It might be possibility to extract the whole spectrum of negative ions by subtracting the positive ion spectrum measured with a grid in the ion beam. It is difficult to connect the ion species to the corresponding signal peak as the accelerating potential is unknown.

The origin of the underlying acceleration mechanism for the ions is not yet fully understood. The thermal expansion as a source for the acceleration can be excluded as the ions are relatively cold in the discharge



(a) (b)

Figure 13. Velocity profile measured with an E×B probe in SF_6 and a magnetic field of 170 G without acceleration grids. The profiles were measured at 6 sccm SF_6 flow rate at a pressure of $3 \cdot 10^{-4}$ mbar-N_2 for a input power of (a) 200 W and (b) varying powers.

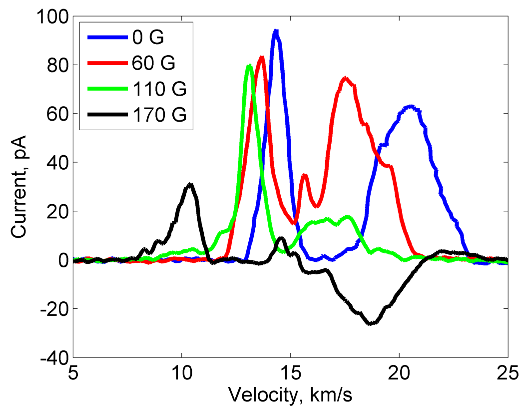


Figure 14. Measurements with the E×B probe in a 6 sccm SF_6 plasma at a pressure of $3 \cdot 10^{-4}$ mbar-N_2 and a power of 200 W for different magnetic field configurations without acceleration grids.

with a temperature of around 0.1 eV.[3,5] In order to reach a velocity of 12 km/s the ions would have to have a temperature of roughly 75 eV assuming a mass of 100 amu. One possible explanation for the velocity is that positive ions get accelerated by a potential drop between the antenna and the ion-ion region downstream the magnetic barrier. Close to the antenna the plasma is electronegative and has a potential of around 30 V which corresponds to the acceleration potential which can be observed in Fig. 13. After crossing the magnetic barrier the positive ions might accelerate negative ions due to ambipolar diffusion.

The magnetic barrier is an essential part of the PEGASES thruster as it increases the negative ion production. Figure 14 show the VDF of the different ion species in a 6 sccm SF_6 plasma at a pressure of $3{\cdot}10^{-4}$ mbar-N_2 and a power of 200 W for several magnetic field configurations. The strength of the magnetic field is measured at center of the PEGASES cavity between the magnets. The plasma potential changes with the different magnetic field layouts inside the discharge cavity. This might be the origin of the shift for the measured velocity distribution functions. A comparison of the spectra shows an increase of the negative ions with an increasing magnetic field strength. Without the magnetic field an positive ion peak can be observed at around 18 km/s. This peak decreases with an increasing magnetic field as more negative ions cancel out the signal produced by the positive ions. This shows that the magnetic barrier is essential for the creation of negative ions.

IV. Conclusion and Perspectives

An E×B probe has been used to investigate the plasma in the plume of the PEGASES thruster. It has been shown that the plasma contains only a small fraction of multiply charged ions in the case of a xenon plasma. The VDF of the ions in the plume of the thruster follows the grid bias as expected when a bias above 200 V is applied. In a xenon plasma above an input power of 100 W no change can be observed in the VDF of the ions. The flow rate and the pressure is an important factor for the PEGASES thruster. At a low flow rate and pressure the E×B probe shows a higher signal strength. A measurement with the E×B probe at different angles shows that the PEGASES thruster with its grids can be considered as a uniform source with an divergence angle higher than 8°. The signal strength of the E×B probe decreases when the probe is moved further away from the source. A small signal peak in front of the main Xe^+ peak has been observed in several cases. This peak has been observed with other thrusters and E×B devices. It probably finds is origin in the probe functioning, however, its existence cannot be explained at the moment.

The measurements performed with SF_6 show the same trend as in xenon, ie. the plasma follows the acceleration bias. The E×B probe has been used to identify different ion species in the plume of the thruster, namely SF_5^+, SF_3^+, SF^+, S^+, F^+. It is possible that other ion species are present and the signal is hidden in the VDF. The measurements which have been performed at the entrance of the cavity with a grid show that the plasma is composed of negative and positive ions. The negative ion density is strongly dependent on the magnetic barrier. The ion density inside the cavity increases with the power. It has been shown that the magnetic field is essential to the production of negative ions.

More measurements will be performed with the E×B probe while simultaneously observing the plasma potential in both xenon and SF_6 plasmas. It is planed to improve the measurements of the negative ions with the E×B probe, however a proper approach has to be developed to identify the different ion species.

V. Acknowledgments

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