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E × B probe measurements in molecular and electronegative plasmas

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This paper reports on the design, the building, the calibration, and the use of a compact E × B probe that acts as a velocity filter or a mass filter for ion species. A series of measurements has been performed in the discharge and in the beam of the PEGASES (Plasma Propulsion with Electronegative GASES) ion source. PEGASES is a unique inductively coupled radio-frequency source able to generate a beam of positive and negative ions when operated with an electronegative gas. In this study, experiments have been carried out with SF6. Calibrated E × B probe spectra indicate that the diagnostic tool can be used to determine the ion velocity and the plasma composition even when many molecular fragments are present. In addition, the probe is able to detect both positive and negative ions. Measurements show a large variety of positively charged ions coming from SF6. Conversely, the beam is solely composed of F− and SF6− negative ions in compliance with computer simulations. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4937604]

I. INTRODUCTION

An E × B probe, also called a Wien filter, is a velocity filter that is based on the drift of charged particles in a region of crossed electric and magnetic fields.1,2 Such a diagnostic tool has often been used to determine the positive ion velocity and the multiply charged ion fraction in ion sources and in the beam of electric thruster for spacecraft.

In this contribution, we report on the building, the calibration, and use of an E × B probe in molecular and electronegative plasmas. The main objective of this work is to demonstrate that an E × B probe, when accurately calibrated, can be employed instead of a mass spectrometer to access the ion energy, the ion charge state, and the composition of a plasma discharge, both in electropositive and electronegative gases. An E × B probe offers several advantages, which make it a smart ion probe in the field of plasma physics. It can be installed inside a vacuum chamber with ease. It can be moved with translation stages, which allow for spatially resolved measurements. It is easy to operate. Moreover, it is inexpensive. Here, E × B probe measurements were carried out in the discharge and in the beam of the plasma propulsion with electronegative GASES (PEGASES) ion source.3–12 PEGASES is an unconventional gridded ion source concept for spacecraft propulsion as primary purpose. The source was operated either with noble gases or with molecular gases. The production of a large amount of negative ions was achieved with SF6.

The paper is organized as follows. Section II describes the gridded radio-frequency (RF) PEGASES ion source. Section III is devoted to the E × B probe. First, the probe theory and working principle are given. Second, we describe the instrument architecture as well as the complete experimental arrangement. Finally, the procedure for calibrating the probe is explained and exemplified. Calibration consists in determining the relationship between the recorded velocity and the true ion velocity at the probe entrance. Section IV reports on measurements performed in a positive ion beam created from a sulfur hexafluoride (SF6) discharge. Section V contains measurements in a plasma and a beam containing positive and negative ions. Conclusions are drawn in Section VI where future works are also discussed.

II. THE PEGASES ION SOURCE

The PEGASES is an unconventional gridded ion source concept for which the discharge is created in a strongly electronegative gas.8–13 Instead of creating and accelerating positive ions only, PEGASES ejects pair of positive and negative ions. PEGASES is foreseen as an innovative ion thruster for propulsion of satellites and spacecraft. The ionization stage of PEGASES can be divided into two main parts. In a first section, an inductively coupled RF discharge is produced with an electronegative gas such as dioxygen (O2), SF6, and di-iodine (I2) in a rectangular dielectric cavity. An electronegative plasma that contains electrons as well as positive and negative ions therefore fills the back of the cavity. In a second section, the electronegative plasma is transformed into an electron-free plasma, i.e., an ion-ion plasma,14 through a magnetic filter.15 Electrons are trapped into the region of strong magnetic field. Due to collisions with neutral heavy particles, the electron temperature quickly drops. Subsequently, cold electrons attach to molecules to form negative ions. Afterwards, the ion-ion plasma is electrostatically accelerated through an assembly of two polarized grids. The sign of the potential of the first grid is changed periodically to eject the two ion species in turns.11,12 The second grid is kept at ground. Thanks to its specific design, PEGASES offers three advantages over conventional thrusters. First, as both positive and negative ions are expelled out of the thruster, an external neutralizer is not necessary, which increases the reliability level. Second, the downstream

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recombination of positive and negative ion pairs is relatively fast, which guarantees a low charged-particle density in the beam. As a consequence, interaction between the charged particles and the spacecraft surfaces is drastically reduced. Finally, a promising propellant for PEGASES is I\(_2\), a strongly electronegative gas, which can easily be stored in solid state under space flight conditions.\(^\text{16}\) The propellant storage volume is then strongly reduced, an important aspect for any space vehicle.

A drawing of the PEGASES thruster is shown in Fig. 1. The discharge is produced in a rectangular BN-SiO\(_2\) cavity by the way of a 4.2 MHz planar antenna embedded into a ferrite shield. As the cavity is dielectric, the plasma is floating. The input RF power ranges between 80 W and 250 W. Permanent samarium-cobalt (SmCo) magnets are used to generate the transverse magnetic field of the filter. The magnitude of the field can be varied from 0 to 340 G by changing the number of magnet bars. 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 can be found in references\(^\text{8,9,11,15}\).

Without the magnetic filter section, PEGASES can naturally be operated as a conventional gridded ion engine with noble gases like Xe, Kr, and Ar. The ion beam must then be neutralized with an electron stream to obtain a quasi-neutral plasma downstream the grids. A large current extraction and a low beam divergence angle can only be reached by avoiding Coulomb repulsion between positive ions. A negatively polarized heated tungsten filament was used in this study as an electron source.

III. E \times B PROBE

A. Principle

An E \times B probe, also called a Wien filter, is a diagnostic tool that allows to measure ion velocity in a given direction\(^\text{1-7}\). A schematic drawing of an E \times B probe is presented in Fig. 2.

The basic principle of the probe relies on the drift of a charged particle in crossed electric and magnetic fields. The motion of ions in a collisionless medium with electric and magnetic fields is described by the Lorenz force \(F_L\),

\[
F_L = ze(E + v \times B),
\]

where \(e\) is the elementary charge, \(Z\) is the charge state, \(E\) and \(B\) are the electric and magnetic fields, respectively, and \(v\) is the ion velocity vector. The Wien filter discriminates particles with distinct velocity. When the particles undergo no force because magnetic and electric interactions are balanced, i.e., the Lorentz force is null (\(F_L = 0\)), Equation (1) becomes

\[
E = -v \times B = B \times v.
\]

This shows that a charged-particle with the velocity \(v_x\) moves along a straight line in the \(x\) direction in the region, wherein \(E\) and \(B\) are perpendicular. In other words, the particle trajectory is not deflected in this region.

According to the theory, an E \times B probe is therefore composed of two main elements. Two narrow apertures define a line: \(x\) direction. The segment between the two apertures is placed in a cross-field region where the electric field \(E_y\) is orthogonal to the magnetic field \(B_z\), the so-called cross-field configuration, Equation (2), reads

\[
v_x = \frac{E_y}{B_z}.
\]

Equation (3) can then be expressed in the form

\[
v_x = \frac{2U}{Bd}.
\]
The velocity $v_s$ is therefore selected by adjusting the electrode bias voltage $U$. Sweeping the electrode voltage $U$ across an appropriate range, while monitoring the transmitted ion current leads to a current-voltage characteristic curve that is related to the ion velocity distribution function.

Although Equations (3) and (4) indicate the velocity $v_s$, does not depend on the charge state $Z$, an $E \times B$ probe allows to discriminate between singly charged and multiply charged ion species, contrary to a Repulsing Potential Analyzer (RPA). The latter filters ions according to the ratio $V/Z$, where $V$ is the experienced potential drop. When ions with a different charge state are accelerated through the same potential drop, which is the case in most ion sources and in electrostatic thrusters like gridded ion engines and Hall thrusters, a RPA cannot distinguish between the various $Z$. On the contrary, as the velocity is proportional to the square root of $Z$, an $E \times B$ probe can separate ion species with a different charge state.

### B. Instrument

Figure 3 shows a cross-sectional view of the $E \times B$ probe developed and constructed for studying the ion beam of various electrical thrusters. The static magnetic field inside the filter section is produced using bars of permanent SmCo magnets mounted in north-south configuration. A magnetic circuit permits to increase the strength of the $B$ field inside the drift section and to make it homogeneous and symmetrical. The circuit consists in 4 screens in magnetic stainless steel placed around the magnet bars. The screen also serves as probe body. The measured field magnitude along the axis of the filter is 1660 G. The electric field is established between two planar electrodes in aluminum. The electrodes are inserted between the magnet bars in such a way that $E$ is orthogonal to $B$. A 1 mm thick Teflon foil is used to electrically insulate the electrodes from the magnets and the magnet supports, as illustrated in Fig. 3. The gap $d$ between the two electrodes is 16.0 mm. The length of the magnets, the electrodes, and subsequently the drift section is 150 mm. The entrance collimator of the probe is a long quartz tube with a small inner diameter. The diameter and length of the tube can easily be changed to optimize the resolution, i.e., the ability to discern two consecutive peaks, as well as the current level. The entrance collimator geometry is 27 mm in length, inner diameter of 1.4 mm, and outer diameter of 4 mm. The exit collimator consists of a stainless steel plate with a small aperture to let the ions go through. The resolution and signal strength can be optimized by changing the aperture diameter. The mounted aperture has a diameter of 2.4 mm. It is important for the probe to operate properly that the entrance and exit collimators are perfectly aligned. The acceptance angle of the probe is 6°. It is the largest angle at which the ions can arrive and still pass the entrance collimator. The collector is a graphite cone inserted in a graphite tube. The design aims at minimizing the influence of secondary electron emission as well as at reducing the sputtering yield and the filter section contamination. The collector is electrically isolated from the surroundings by a Teflon holder. The collector is placed 95 mm behind the exit aperture. Finally, the probe dimensions, without entrance collimator are $290 \text{ mm} \times 58 \text{ mm} \times 58$ mm. The probe mass is 3.5 kg.

The resolution of an $E \times B$ probe depends on the filter section length, collimator geometry, electrode shape, and magnetic field strength. For instance, long and narrow collimators lead to a high resolution. In return, the ion current is low and amplification may be needed. From Eq. (4), the relationship between the velocity resolution and the magnetic field reads for a given electric field,

$$
\Delta v = \frac{2}{Bd} \Delta U,
$$

where $\Delta U$ is the voltage step. Equation (5) shows that the resolution improves when the $B$ field magnitude increases. However, at large $B$, the Larmor radius is small, i.e., ions are magnetized and their trajectory inside the filter section is altered. Accurate optimization of an $E \times B$ probe therefore necessitates numerical simulation of the ion trajectories as a function of the probe configuration. Note that as the magnetic field magnitude is fixed, a probe can only be optimized for a narrow range of atomic masses.

The electrodes are powered using a symmetrical power supply based on two 3 W output power high-voltage modules. A module is able to deliver a voltage up to 300 V with positive or negative polarity. The maximum velocity of the filter is therefore 225.9 km/s, which corresponds to an accelerating potential of 34.8 kV for xenon and 10.6 kV for argon. The lowest available voltage step is 0.2 V, i.e., 75 m/s. The current collected by the graphite collector is accurately measured using a calibrated Keithley 6485 picoamperemeter. The device is directly connected to the collector interface. The current range is 2 nA–20 mA. The resolution is 10 fA at 2 nA and the accuracy is 0.4%. The wiring is composed of three 50 $\Omega$ RG316/u type coaxial cables with SMA connectors on the probe side and BNC on the vacuum feedthrough side. A computer-controlled interface has been developed for control and automation of the probe and for data acquisition. The interface relies on a 16-bit 250 kS/s NI DAQ 6211-USB card.

### C. Setup and current trace

Experiments with the $E \times B$ probe system and the PEGASES ion source were carried out with the EPIC (Electric Propulsion Innovative Concepts) test bench. The stainless steel vacuum tank is 0.4 m in diameter and 0.75 m long. It is evacuated by a 1000 l/s in nitrogen turbomolecular pump connected to a 65 m$^3$/h primary pump. The chamber has several optical windows, access ports, and electrical feedthroughs. It can be equipped with a variety of probes and...
linear motion stages. A base pressure down to $10^{-6}$ mbar-N$_2$ is reached without gas inlet. The background pressure at a gas flow rates of 20 SCCM is typically a few $10^{-4}$ mbar-N$_2$ depending on the gas. Figure 4 depicts a layout of the experimental arrangement showing the gridded source, the probe, and the electrical connections. A heated tungsten filament polarized at $-35$ V was used as an ion beam neutralizer when PEGASES was operated as a positive ion source. The probe was installed on a translation stage moving in the $x$ axial direction. It was aligned along the source axis. The probe body was grounded.

Two raw $E \times B$ spectra obtained by sweeping the electrode voltage, while recording the ion current are shown in Fig. 5. The xenon and krypton spectra were recorded along the source axis in the ion beam at $x = 20$ cm. Each spectrum corresponds to the ions Velocity Distribution Function (VDF) in the probe direction. In the two cases, the source was operated at 150 W transmitted RF power and 300 V applied on the screen grid. The mass flow rates were 2.5 SCCM for Xe and 10 SCCM for Kr. Singly and doubly charged ions are detected for the two gases. The beam, however, mainly contains singly charged ions. Current traces in Fig. 5 indicate that the typical current level is within the nA range.

The detection limit is 10 pA and the signal-to-noise ratio is typically above 1000.

**D. Calibration**

Equation (4) describes the ideal case. A more realistic treatment can account for the finite size apertures of the probe. The Newton’s second law of motion gives the particle acceleration inside the $E \times B$ drift region. Only the vertical acceleration $a_y$ is considered here. Moreover, the velocity is assumed to be in the $x$ direction only. A rigorous treatment, however, must account for the three components of all vectors. Under our assumptions, the acceleration reads

$$a_y \approx \frac{Ze}{m} (E_y - v_x B_z) \approx \frac{Ze}{md} (2U - v_x B_d). \quad (6)$$

The acceleration is also retrieved from the fact that the charged particle trajectory is a parabola inside the filter,

$$a_y \approx \frac{2h}{L^2} v_x^2, \quad (7)$$

where $L$ is the length of the drift region and $h$ is the off-axis misalignment at the end of the filter, i.e., the difference between the ion $y$ coordinate at the entrance and at the exit of the drift region for an ion entering with a 0° angle. A governing equation of the $E \times B$ probe is then

$$h = \frac{Ze L^2}{2md v_x^2} (2U - v_x B_d). \quad (8)$$

In the case of an ideal probe, there is no net force, i.e., $a_y = 0$, the velocity is given by Eq. (4) and $h = 0$, i.e., the apertures are assumed infinitely narrow. Departure from an ideal probe behavior has several possible origins: irregular magnetic and electric fields, edge effects at the entrance and exit of the drift section, misalignment, pressure level inside the device (collisions), accumulation of charges, finite size of the apertures as previously discussed, and non-zero entrance angle. Eq. (4) is therefore a strong approximation for the ion velocity. Although the non-linear relation in Eq. (8) gives a better estimate for $v_x$, it does not account for all defects. It is therefore of no practical use for spectrum analysis. One way to account for departure from the ideal case consists in considering the probe apparatus profile. Lim and co-workers recently proposed a rigorous approach based on computer simulations. They compute the transfer function of the probe that best fits to the measured profiles when accounting for the whole ion VDF. In this work, a more simple approach based on measurements has been selected. The true ion velocity is assumed to be connected to the measured velocity through an $\alpha$ coefficient

$$v_{\text{measured}} = \alpha v_{\text{true}}. \quad (9)$$

For an ideal probe, $\alpha$ is equal to 1. Using Eq. (4), the corrected velocity reads

$$v_{\text{true}} = \frac{1}{\alpha} \frac{2U_m}{B_d}, \quad (10)$$

where $2U_m$ is the probe voltage of the peak center. This relatively simple approach is of interest as the $\alpha$ parameter can be experimentally determined for a given probe configuration.
when \( v_{\text{true}} \) is known. Indeed, \( \alpha \) can be written as

\[
\alpha = \frac{\sqrt{2m}}{ZeU_{\text{acc}} BD^2} \tag{11}
\]

where \( U_{\text{acc}} \) is the potential drop experienced by the ion species between creation region and entrance of the probe. The latter is determined with a cylindrical Langmuir probe by measuring the plasma potential inside the source cavity and at the probe entrance. The \( \alpha \) calibration factor of the probe has been determined for various gases: Xe, Kr, Ar, and O\(_2\). Results are summarized in Fig. 6. Several conclusions can be drawn from the graph. The \( \alpha \) factor is above one for our probe configuration. It increases with the velocity. The apparent impact of the charge-state might be due the high velocity of multiply charged ion species. Another interesting feature is the fact that \( \alpha \) depends on the ion mass, as can be seen in Fig. 6. For a given accelerating potential, \( \alpha \) is found to decrease with the mass. We observed the same trend for the evolution of \( \alpha \) with the mass from numerical simulations of the ion trajectory through the E × B probe drift region performed with the COMSOL multiphysics software. Although Eq. (4) is mass independent, the effect appears with a more rigorous treatment of the ion trajectory, see Eq. (8). To sum up, the experimental calibration of the E × B probe shows that the \( \alpha \) parameter is actually a function of both the velocity and the mass,

\[
\alpha = \alpha(v, m). \tag{12}
\]

An example of a calibrated spectrum is given in Fig. 7 for Xe. Calibration has been achieved using a linear relation for \( \alpha \) as a function of \( v \) derived from experimental data. The calibrated spectrum is shifted towards the low velocity side. A first peak (Xe\(^+\)) is detected at 20.3 km/s and a second peak (Xe\(^{2+}\)) at 29.3 km/s. The velocity ratio is 1.44, i.e., close to \( \sqrt{2} \) as expected. The accelerating potential, or beam energy, is 281 V, somewhat below the acceleration voltage. The uncertainty in the measurement of the velocity can be obtained from relation (10) using the total derivative.\textsuperscript{17} The relative uncertainty \( \Delta v / v \) is around 0.14 for the velocity range of interest in this study. The error bars associated with the quantities involved in the determination of the velocity were estimated: \( \Delta U = 0.1 \) V, \( \Delta B = 10 \) G, \( \Delta d = 0.5 \) mm, and \( \Delta \alpha = 0.1 \). The latter was inferred from a statistical analysis.

## IV. POSITIVE ION BEAM IN SF\(_6\)

SF\(_6\) is currently employed as a propellant for the development stage of the PEGASES prototype. The SF\(_6\) molecule is heavy (146 amu), strongly electronegative, and it has a low ionization threshold. Moreover, SF\(_6\) is nontoxic, non-flammable, and inexpensive. The SF\(_6\) molecule is nevertheless relatively complex, that means it forms many molecular fragments in plasma state.

Although the chemistry of SF\(_6\) discharges is well documented, experiments and modeling show that the plasma composition strongly depends on various parameters like the power level and the pressure. As available data cannot be extrapolated, the PEGASES discharge has to be diagnosed. SF\(_6\) discharges have often been examined with mass spectrometry to find the plasma composition and the energy of molecular fragments.\textsuperscript{18-21} Mass spectrometry is, however, a cumbersome diagnostic technique. In this work, the beam of the PEGASES source has been investigated with an E × B probe instead.

A calibrated mass spectrum obtained in the beam of PEGASES operated with SF\(_6\) is depicted in Fig. 8. The operating conditions were 4 SCCM SF\(_6\) flow rate, 120 G magnetic field strength, and 300 V applied on the screen grid. The transmitted RF power reached 210 W with a Power Transfer Efficiency (PTE) of 0.6. The x-axis was calibrated using a linear relation for the mass-dependent \( \alpha \) factor deduced from the data set shown in Fig. 6 for a 300 V accelerating voltage. The spectrum reveals the plasma complexity in terms of species. Fragments are well identified from B\(^+\) to SF\(^+\). Heavy ions are SF\(_{5}^+, SF_{4}^+, SF_3^+, \) and W. However, peaks corresponding to SF\(_{5}^+, SF_{3}^+, SF_2^+, \) and W atoms are produced by the external hot filament that acts as a neutralizer. The observation of a W\(^+\) peak indicates a certain amount of W particles enter the source, are ionized, and then experience the potential drop. The SF\(_{5}^+\) signal indicates
FIG. 8. Distribution of positive ions by mass in the PEGASES beam with a pure SF$_6$ discharge (4 SCCM, 120 G, 210 W, 300 V, PTE = 0.6, and x = 20 cm).

that the SF$_6$ molecule is not fully dissociated in this case. The presence of S is confirmed by the formation of a sulfur coating on the walls of the vacuum chamber. As can be seen in Fig. 8, the mass spectrum exhibits peaks of B$^+$, N$^+$, O$^+$, O$^{2+}$, and Si$^+$ ions. These species are not detected with noble gases, which rules out any air infiltration. They originate from the cavity wall material as a result of a chemical attack by F-containing radicals. Finally, Fig. 8 demonstrates that the resolution of a calibrated E × B probe is satisfactory when used as a mass selector.

The shape of mass spectra recorded in the positive ion beam of the source with SF$_6$ is not much affected by the operating conditions. The main features of every spectrum remain: there is no dominant positive ion, full dissociation is never reached, and impurities from the cavity dielectric walls are present. This information is of relevance for modelling of the PEGASES discharge, for analysis of Langmuir probe I-V characteristics, and for thruster optimization. Figure 9 shows normalized mass spectra measured with SF$_6$ for three grid voltages. As aforementioned, the spectrum envelope stays unchanged but the peak intensity ratio varies. SF$_5^+$, SF$_4^+$, and SF$_3^+$ ions are not identified here, but corresponding signal could contribute to the broad peak around 80 amu.

V. ION-ION PLASMA

A. Plasma expansion

One way to observe negative ions in the PEGASES source avoiding the neutralization issue is to probe the plasma ahead of the acceleration system. Hence, measurements were performed with the screen grid mounted to keep a sufficiently high pressure inside the cavity in order to warrant an efficient ion production. The grid was grounded in the experiments. The E × B probe entrance collimator was positioned on-axis at the grid plane. A 2.8 cm in diameter hole through the grid allowed the probe to collect ions.

A typical E × B spectrum recorded in pure SF$_6$ behind the magnetic filter without acceleration is shown in Fig. 10. Under these conditions, the plasma is strongly electronegative as the Langmuir probe I-V curve is almost symmetrical. The trace in Fig. 10 reveals the presence of both positive and negative ion species. The trace shows that the plasma is not symmetrical, i.e., it is not composed of identical positive and negative ions with the same mass and the same temperature. In that case, the net ion current would be zero. The measured velocity of the two ion species is surprisingly high in Fig. 10 since the acceleration system is turned off. Thermal expansion as the mechanism responsible for the high velocity can be excluded. In order to reach a velocity of ∼12 km/s, F$^+$ ions would need a temperature of roughly 6 eV and SF$^+_6$ of about 25 eV, whereas ions are cold in the final section of the discharge.

In fact, the positive and negative ions diffuse out of the source because the downstream potential is below their thermal speed. The measured ion velocity simply images a large $\alpha$ parameter. A reasonable estimate for the potential drop is ∼1 eV as background electrons are cold and the chamber walls are grounded. Assuming the negative peak in Fig. 10 can be attributed to F$^-$ ions (the dominant negative ion species; see Section V B), Eq. (11) can be used to determine the value of $\alpha$. One finds $\alpha = 5.9$. A high $\alpha$ indicates that the...
The probe is not optimized for a low particle velocity, in agreement with ion trajectory calculations with COMSOL. $\alpha$ can then be used to correct the velocity axis of the graph in Fig. 10. As a consequence, ions can be present without being detected by the probe when the associated current is cancelled by a current of ions with the opposite charge. A current is therefore measured only in two conditions: ions exist with no corresponding ions with the opposite charge and the density of a given ion is above the density of the opposite ion.

The formation of negative ions is enhanced by a low electron temperature. In order to reduce the temperature, the pressure inside the cavity and the magnetic field strength must be optimized. Figure 11 illustrates the evolution of the $E \times B$ spectrum with the magnetic field intensity. The SF$_6$ flow rate is kept fixed at 6 SCCM. A negative ion peak is only visible for the largest magnetic field magnitude. Figure 11 suggests two things: (i) a large negative ion density is only achieved with a relatively strong magnetic field, in agreement with Langmuir probe measurements and (ii) negative ions can diffuse freely only when the plasma becomes strongly electronegative.

**B. Beam of positive and negative ions**

An extraction scheme based on an alternate positive and negative grid voltage has been proven successful for the PEGASES concept when an electron-free plasma state is reached. Positive and negative ions are extracted and accelerated periodically in such a way that the downstream beam neutralization is continuously maintained. In this work, the first (screen) grid is polarized with a square-wave voltage, while the second (acceleration) grid is grounded. The homemade power supply is able to provide a voltage amplitude up to ±1000 V with a frequency up to 37 kHz. The modulation frequency is much below the ion plasma frequency, i.e., the plasma response can be considered as DC. Due to the low square-wave frequency, the downstream neutralization is not complete, but positive and negative ions can nevertheless be extracted and therefore detected by the $E \times B$ probe.

Figure 12 presents an $E \times B$ spectrum recorded in the beam of PEGASES with SF$_6$. The probe was placed on the thruster axis 20 cm behind the second grid. The operating conditions were 6 SCCM SF$_6$, 190 G, and 180 W. A voltage amplitude of ±250 V was applied on the screen grid at a frequency of 1 kHz. The square-wave duty cycle was fixed at 50%. Measurements were time-averaged meaning the current was continuously measured with a probe voltage sweep frequency lower than the square-wave frequency. Spectra similar to the one in Fig. 12 were obtained for other bias voltages and higher frequencies. F$^-$ and SF$_6^-$ are the only negative ions observed in Fig. 12. F$^-$ is the dominant negative ions, in compliance with numerical simulation outcomes and laser photodetachment experiments. Several positive fragments are detected. The positive ion spectrum is similar to the one obtained in a positive ion beam, excepted for the F$^+$ peak.

The two spectra in Fig. 13 were recorded under previous experimental conditions. The extraction scheme was, however, different in order to separate the contribution of positive and negative ions.
negative ions. Positive ions were captured with a [±250 to 0] V screen grid potential, whereas negative ions were captured with a [–250 to 0] V potential. The square-wave frequency was 1 kHz with a 50% duty cycle. Interestingly, in Fig. 13, negative ions can be extracted without applying a high positive bias voltage on the screen grid. One possible explanation is the diffusion of the entire plasma through the grid assembly when the screen grid is biased at 0 V, therefore providing the positive charges necessary for beam neutralization. The mechanism is also valid for the extraction of positive ions, negative charges being supplied at 0 V in that case.

Figure 14 displays the E × B signal as a function of the ±250 V square-wave duty cycle at 1 kHz. As expected, the negative ion signal decreases when the duty cycle increases and conversely for positive ions. The graph also shows that the positive and negative ion currents are not equal at a duty cycle of 50%. This fact is also visible in Figs. 12 and 13. Two possible reasons can be given. The formation of a sulfur-containing insulating coating on the screen grid during extraction of positive ions reduces the acceleration potential in time, as observed in Ref. 26. Or a certain amount of electrons are co-extracted with the negative ions due to a non-optimized grid system and/or current leakage. For our set of operating conditions, an equal current level for the two ion species can be achieved with a duty cycle below 30%. A graph similar to the one shown in Fig. 14 has been obtained from repulsing potential analyzer measurements in the PEGASES beam at a square-wave frequency of 200 kHz by Lafleur and co-workers.12 Their measurements also reveal an unbalanced ion beam at a 50% duty cycle. The two experiments, however, indicate that the ion currents, therefore the downstream beam neutralization, can be controlled by tuning the duty cycle of the grid voltage waveform, an important aspect for space propulsion applications.

VI. CONCLUSION

E × B probe measurements have been performed in the discharge and in the beam of the PEGASES ion source operating with SF$_6$. The experiments show that the probe can be used to determine the ion velocity and to identify positively and negatively charged ion fragments.

E × B probe spectra show a large variety of positively charged ions coming from SF$_6$ as well as ions resulting from the chemical erosion of the BN-SiO$_2$ cavity walls. The dominant negative ions in the beam are F$^-$ and SF$_6^-$ in compliance with computer simulations and recent laser photodetachment experiments. Furthermore, the results confirm two key points for spacecraft propulsion purpose. First, alternate extraction of positive and negative ions is achieved by applying a square-wave voltage on the screen grid. Second, the downstream ion current, that is the beam neutralization, can be controlled by adjusting the square-wave duty cycle.

Further experiments now consist in performing time-resolved E × B probe measurements in the PEGASES beam during one period of the voltage square-wave applied on the screen grid. Of particular interest is the change in the E × B spectrum when switching from a positive to a negative voltage and vice versa. Investigation of the influence of the wave frequency and duty cycle upon the ion dynamics and plasma composition is another point of great interest.

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