Plasma Propulsion with electronegative gases

IEPC-2009-001

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

Ane Aanesland[*], Lara Popelier[†], Gary Leray[‡], Pascal Chabert[§]
Laboratoire de Physique des Plasmas, CNRS - Ecole Polytechnique, 91128 Palaiseau, France

Stéphane Mazouffre[**] and Dennis Gerst[††]
Institut de Combustion Aérothermique Réactivité et Environnement, CNRS, 45071 Orleans , France

Abstract: A new concept of plasma propulsion, patented by the Ecole Polytechnique in France in 2007, is currently being developed in our laboratories and carries the name PEGASES for Plasma propulsion with Electronegative GASES. The PEGASES thruster exploits an ion-ion plasma (electron-free plasma) from which both positively and negatively charged ions are extracted and accelerated to provide thrust. The efficient recombination rate between the oppositely charged ions provides a fast beam mostly composed of neutral particles downstream of the thruster without the need of an additional electron-emitting neutralization system.

Nomenclature

α = negative ion fraction, i.e. ratio between the negative ion and electron density
T_e = electron temperature
X = position perpendicular to the magnetic field

I. Introduction

IN CLASSICAL electrostatic and electromagnetic thrusters, the thrust is provided solely by extracting and accelerating positively charged ions. Electrons are emitted from an additional neutralization source (a cathode) to neutralize the ion beam and avoid a charge built up on the spacecraft. This electron-emitting cathode limits to a large extent, the performance and life of both ion and Hall thrusters[1], and large efforts are made to increase their performance and lifetime. Simultaneously, efforts are devoted towards the development of new concepts where the neutralizer is not needed.

For commercial use the conventional chemical propulsion systems are in many circumstances still preferred over the electrostatic and electromagnetic thrusters[1]. One constrain in using plasma propulsion is the possible damage from the plasma plume due to backscattering of ions and electrons onto the host spacecraft. This backscattering can for example damage the solar panels, erode the acceleration grids or interfere with on board instruments.

The PEGASES concept[2-4] presented here provides two main advantages over existing plasma propulsion systems: i) There is no need for an additional electron neutralization system as an equal amount of positive and negative charge are extracted from the plasma. ii) The possible damage from charged particles outside of the thruster

---

[*] Research Scientist at CNRS, Ecole Polytechnique, ane.aanesland@lpp.polytechnique.fr
[†] PhD student, Ecole Polytechnique, lara.popelier@lpp.polytechnique.fr
[‡] PhD student, Ecole Polytechnique, gary.leray@lpp.polytechnique.fr
[§] Research Scientist at CNRS, Ecole Polytechnique, pascal.chabert@lpp.polytechnique.fr
[**] Research Scientist at CNRS, ICARE, Stephane.Mazouffre@cnrs-orleans.fr
[††] Aerospace engineer student, ICARE, dennis.gerst@googlemail.com

body (on the host spacecraft) is drastically reduced because positive and negative ions recombine very efficiently and form quickly a beam mostly composed of neutral particles downstream of the thruster.

II. The PEGASES concept

The PEGASES concept is illustrated in figure 1. In short, an electronegative gas is used as propellant such that the plasma exited by radio frequency power in the MHz rage consists of both positively and negatively charged ions in addition to electrons. A magnetic field, with field-lines perpendicular to the extraction and acceleration axis and with a magnitude of about 200 G, is applied to filter away the electrons. This electron filtering, described with a fluid model[5], allows a stratification of the plasma such that an electron-free region, i.e. an ion-ion plasma, occurs in the extraction zone. The ions of opposite charge are (from this electron-free region) extracted and accelerated separately in space or in time. Several methods of extraction are investigated using biased grids as well as gridless extraction, the main goal being an equal number of negatively and positively charged particles extracted and accelerated from the plasma.

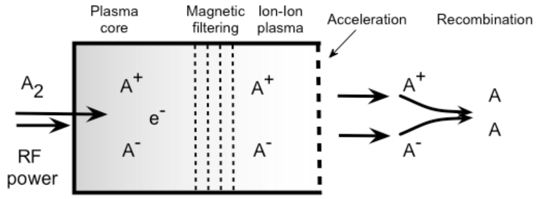

Figure 1 The PEGASES concept

A. Prototype 1

A drawing of the prototype installed inside a 2 m long and 1 m in diameter vacuum facility is shown in Figure 2. The plasma is exited in a long cylinder, 5 cm in diameter and 20 cm long, by a three-loop antenna powered by 13.56 MHz. A tunable matching network is used to match the plasma impedance to the 50 Ω output impedance of the power supply. The cylinder is of quartz and terminated at the ends by metallic plates, which can be grounded, floating or biased to a desired potential. The electronegative gas is typically oxygen or SF_6 and is introduced in the plasma core in the centre of the rf antenna. A magnetic field parallel to the cylinder axis is generated by four solenoids separated by 5 cm. A current of about 2 A produce a magnetic field of about 200 G on axis. Two extractors are placed perpendicular to the cylinder axis, i.e. perpendicular to the magnetic field lines. The extractors are each 4 cm long with a cross section of 16 cm^2. The two-extractor system was originally intended for separate extraction and acceleration of positive and negative ions. However, we have come to the conclusion that this is not such a good idea as the two ion beams will blow up on its own space charge before being recombined downstream; this would lead to a low directional beam and reduced thrust. Other drawbacks are the difficulty in up scaling and the small extractor area compared to the thruster body. Our new approach is to extract and accelerate the positive and negative ions from the same extractor with a time varying grid system.

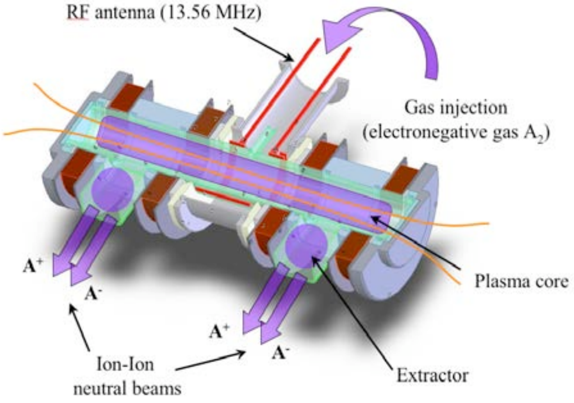

Figure 3 Drawing of the PEGASES prototype

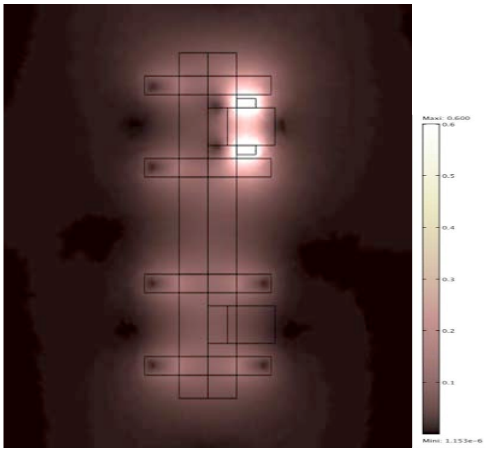

Figure 2 Magnitude of the magnetic field.

III. Results

One of the most important aspects of the PEGASES concept is to create a high-density ion-ion plasma from which the positively and negatively charged ions are extracted. It has been shown previously that an ion-ion plasma can be formed at the periphery of a magnetized electronegative plasma using a large Helicon reactor with a diameter of 30 cm[6]. The PEGASES thruster operates with the same magnetic field strength as in the Helicon reactor, however the extractors are placed at a radius of only 2.5 cm. Measurements of the negative ion fraction α (i.e. the ratio between the negative ion and electron densities) with a moderate magnetic field, showed that the maximum value of α obtained was about 30 in the extractor[3,4]. Hence, a strong electronegative region was reached, but the dynamics of the negatively charged particles were still influenced by the mobile electrons and not only by the heavy ions. The following two methods can be used in order to create an ion-ion plasma in the extractor and increase the performance of the PEGASES thruster.

B. Ion-ion plasma formation with strong magnetic barrier

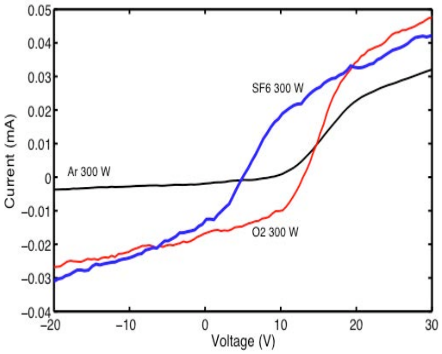

Figure 4 Langmuir probe characteristics in the extractor for argon, oxygen and SF_6.

Permanent magnets placed at the entrance of the extractor provide a strong local magnetic barrier of about 2000 G and increases the confinement of the electrons in the plasma core region. The magnitude of the magnetic field, with permanent magnets at one of the extractors is shown on Figure 3. Figure 4 shows Langmuir probe characteristics obtained in Argon, Oxygen and SF_6 and measured in the extractor where the permanent magnets are placed (represent the top extractor in Figure 3). In the case where an electropositive gas is used such as Argon, both the ion and electron mobility perpendicular to the field is dramatically reduced in order to keep the quasi-neutrality nature of the plasma. This can be seen by the very low ion and electron saturation currents measured in Argon, other vice the probe characteristic is classical with a large electron current compared to ion current. In the case of electronegative gases (O_2 and SF_6) the probe characteristics are symmetrical with an approximately equal saturation current for the positive and negative charges. The symmetrical characteristic is representative for ion-ion plasmas where the current is carried by heavy ions for both positive and negative charges[7]. The ion densities are one order of magnitude larger in the electronegative case compared to the electropositive because the perpendicular ion mobility is increased due to the presence of negative ions (which ensure the quasi-neutrality).

C. Ion-ion plasma formation with dual gas injection

The moderate magnetic field generated by the four solenoids is not strong enough to filter all the electrons away from the extractors. However, this field tailors the electron temperature in such a way that a high and low electron temperature region is formed in the plasma core and the extractor, respectively. The electron cooling perpendicular to the magnetic field has been studied in detail in Ref. 8. The production of positively or negatively charged ions are

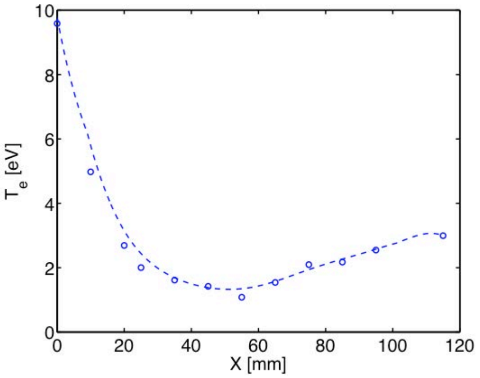

Figure 5 Electron temperature as a function of position perpendicular to the magnetic field.

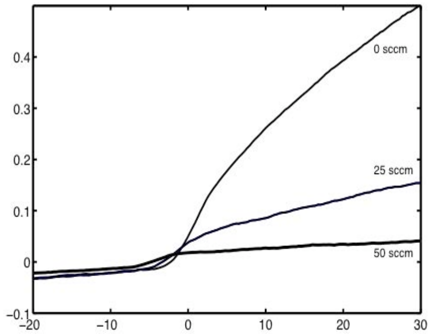

Figure 6 Langmuir probe characteristic for increasing flow in second injection.

strongly dependent on the electron temperature: The attachment rate, creating negative ions by electron-neutral collisions, is for most electronegative gases a decreasing function of T_e while the ionization rate, creating positive ions by electron-neutral collision is an exponentially increasing function of T_e.

Hence, for SF_6 negative ions are mostly created in the region of low electron temperature and dominant when T_e is less than 2 eV. The positive ions are created in the region of high T_e and dominant above 3-6 eV. The electron temperature as a function of position from the plasma core to the exit of the extractor is shown in figure 5 (transition from the plasma cylinder to the extractor is at X=40 mm).

One would expect that the low temperature electrons arriving in the extractor would efficiently attach to neutrals in this region. However, as the neutral gas is introduced in the plasma core where the temperature is high, the neutrals are also exposed to dissociative collisions here. Hence, the neutral gas existing in the extractor is no longer electronegative and an ion-ion plasma can not be obtained. Figure 6, show that an ion-ion plasma is formed in the extractor by introducing a second injection of the electronegative gas in the region where the electron temperature is low. The ion density is of the same order as obtained with a strong magnetic barrier. Further investigation is needed before we can draw a conclusion on the preferred method.

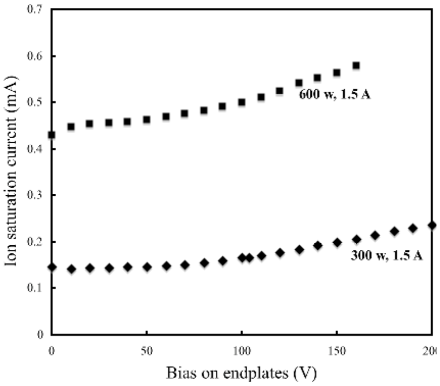

Figure 6 Ion flux out of the extractor as a function of the potential applied to the endplates.

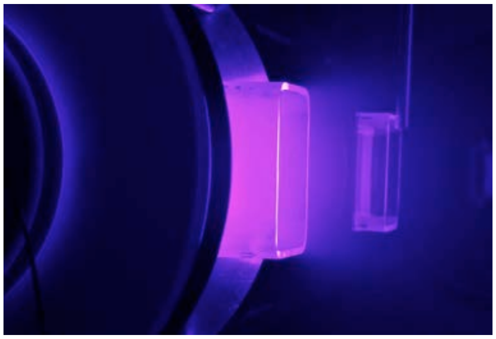

Figure 5 Photo of PEGASES with biased endplates

D. Gridless beam extraction and acceleration

Gridless extraction and acceleration of positive ions from the PEGASES thruster has been investigated. The plasma core, i.e. the plasma cylinder is terminated by metallic end plates. These end plates can be biased to a large positive voltage that pushes the plasma potential up to the desired voltage in a similar manner as the system described in Ref. 9. When the endplates are biased, the plasma inside the thruster is not exposed to ground. In this case one can expect that an electric field is formed from the high potential inside the thruster to the grounded vacuum chamber outside of the extractor. Figure 7 shows preliminary results of the positive ion flux at the exit of the extractor. The ion flux increases with increasing bias voltage on the end plates. Figure 8 shows a photo of the observation. One can be tempted to claim that the increased luminosity in the extractor is due to the acceleration of an ion beam, however the ion energies have not yet been measured so a conclusion is left for the near future.

E. Test bench with cryogenic pumping

A 1.8 m in length and 0.8 m in diameter stainless steel vacuum chamber has been especially designed and constructed at ICARE to carry out experiments in the field of electric propulsion with electronegative gases (Figure 7). The chamber is equipped with a pump stack composed of a large dry pump and a turbo-molecular pump to evacuate light gases like H_2. A cryogenic pump placed at the bottom of the tank (cold head 140T from Oerlikon) allows to get rid of gases like Xe, Kr, O_2, SF_6 with a typical surface temperature of 30 K. Besides, several water-cooled screens are mounted into the chamber to diminish the thermal load reaching the cryogenic surface. Typically, a residual background pressure below 5×10^{-5} mbar is achieved with 1 mg/s SF_6 gas flow rate and 200 W input power. The chamber is equipped with several observation windows, portholes and diagnostic ports. The interior of the facility is easy to access thanks to a large door locate on the front side. The facility does not have a lock-chamber, however, only a few hours are necessary to obtain a high quality vacuum when starting from atmospheric pressure. The test bed, which is named NExET for New Experiments in Electric Propulsion, is dedicated to the examination of physical principles that govern ion-ion thrusters such as ion production, extraction and recombination. The NExET facility will soon be used to test a new PEGASES thruster prototype that originates from innovative works performed at the Ecole Polytechnique.

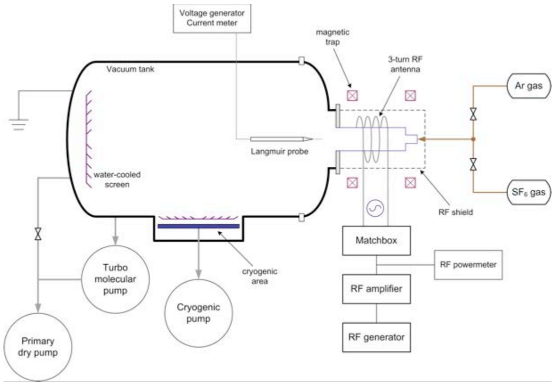

Figure 7 The NExET test bench at ICARE

F. Magnetic trap for ion-ion plasma formation

An inductive RF reactor that can be operated with various gases was built and mounted onto the test facility in order to investigate the ion-ion plasma production from electronegative gases. The reactor consists of a 5 cm in diameter and 30 cm in length quartz tube. The RF power is coupled to the injected gas through a 3-turn copper antenna. The RF frequency can be tuned from 1 MHz up to 100 MHz and the available power can be ramped up until 250 W. An external magnetic trap using small neodymium (Nd-Fe-B alloy) permanent magnets was built to favour the production of negative ions by trapping electrons within the region of high RF power density. The trap was designed to permit a high flexibility level in terms of magnetic field topology. For instance, it is so far possible to create either a radial magnetic barrier (with respect to the plasma flow direction) with a zero-field zone in order to prevent electrons escaping the plasma core (see Fig. 8) or an axial magnetic field topology that confines electrons near the reactor walls. The magnetic field strength can easily be adjusted by varying the numbers of magnets. In all cases, magnetic gradients can be changed on demand by moving magnet holders.

The facility is at present equipped with a compensated Langmuir probe to measure plasma properties. The probe tip, which is a 0.125 mm in diameter and 11 mm long tantalum wire, is located at the outlet of the RF source. A schematic diagram of the entire experimental arrangement is displayed in Fig. 7. Preliminary experiments have been performed to verify operation of the system and to observe the effect of a relatively weak magnetic field in the so-called radial configuration on the ion current. Results obtained with the Langmuir probe for Ar and SF_6 gases are shown in Fig. 9. For the two cases, the gas flow rate is kept fixed at 10 sccm, the RF power is 150 W and the RF frequency is set to 13.9 MHz. The background pressure was $5x10^{-4}$ mBar as the cryogenic pump was not switched on. The downstream plasma density is inferred from the positive ion saturation current measured at a probe voltage of -43 V. As can be seen, the magnetic field magnitude has a little impact upon the density: One would expect a decrease in the plasma density in Argon (with increasing magnetic field) due to the requirement of quasi-neutrality, while in SF_6 negative ions are formed and allows to defuse out of the magnetic trap together with positive ions leading to a constant or weakly decreasing plasma density. The results indicate therefore that the field strength is too small to confine the electrons inside the trap.

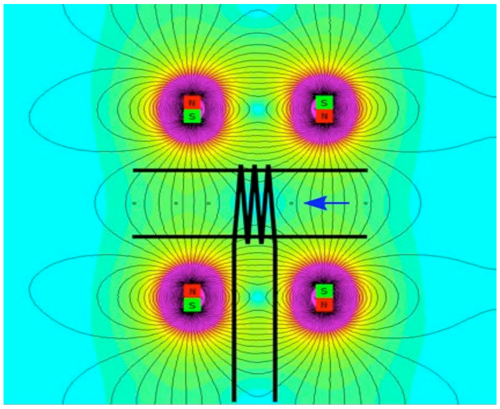

Figure 8 Magnetic field topology of the electron trap calculated using FEMM.

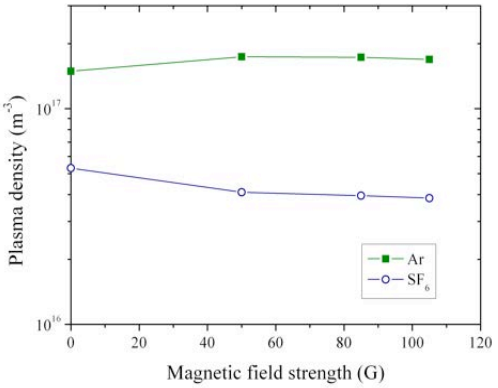

Figure 9 Plasma density measured downstream of the magnetic trap in argon and SF6

IV. Conclusion

Our aim is to develop a new concept for plasma propulsion, which utilize the formation of an ion-ion plasma to accelerate both positively and negatively charged ions for thrust. This concept does not need an additional neutralization system and damage from the plasma plume will be drastically reduced. A progress report is given here, showing the optimization of the ion-ion plasma formation in the extractors. Preliminary results from gridless acceleration indicate a possible ion beam formation. A new test bench with cryogenic pumping facilitiy is being constructed for performance test of the PEGASES thruster. It is however to early for this project to provide values for thrust, specific impulse etc. but we expect to provide these type or results in the near future.

Acknowledgments

The authors are grateful for all the skillful engineering and technical help from J. Guillon (LPP), N. Gouillon (ICARE) and P. Dom (ICARE). We also thank Rodolphe Sarot for the magnetic field calculations of PEGASES presented here (Figure 3). This research was supported by a Marie Curie Intra-European Fellowships within the 6th European Community Framework Program, grant nr: 039757, by the ANR (Agence National de la Recherche) under Contract No. ANR-06-JCJC-0039, and by the EADS Astrium.

References

[1] Goebel, D. M. and Katz, I., “Fundamentals of Electric Propulsion: Ion and Hal l Thrusters”, *Jet Propulsion Laboratory California Institute of Technology,* John Wiley & Sons, 2008.

[2] Chabert, P., “Patent Number,” WO 2007/065915 A1 , 2007.

[3] Aanesland, A., Leray, G. and Chabert, P., “Pegases: Plasma Propulsion with Electronegative Gases”, *44th AIAA Joint Propulsion Conference and Exhibit*, AIAA 2008-5198, 2008.

[4] Aanesland, A., Leray, G. and Chabert, P., “Plasma propulsion with positive and negative ions”, *Journal of propulsion and power*, Submitted March 2009.

[5] G. Leray, G., Chabert, P., Lichtenberg, A. J. and Lieberman, M. A., “Fluid model of an electronegative discharge with magnetized electrons and unmagnetized ions” *J. Phys. D: Appl. Phys*, Vol. 42, 2009.

[6] Corr, C. S., Plihon, N., and Chabert, P., “Transition from unstable electrostatic confinement to stable magnetic confinement in a helicon reactor operating with Ar/SF6 gas mixtures,” Journal of Applied Physics , Vol. 99, No. 10, 2006, pp. 103302.

[7] Woolsey, G.A., Plumb, I.C., Lewis, D.B., “Langmuir probe characteristics in a positive-ion/negative-ion plasma”, *Journal of Physics D Applied Physics* Vol. 6, 1973, pp. 1883-1890.

[8] Kolev S.T., Hagelaar G. J. M, Boeuf J. P., “Particle-in-cell with Monte Carlo collision modeling of the electron and negative hydrogen ion transport across a localized transverse magnetic field”, *Physics of Plasmas*, Vol. 16, No. 4, 2009, pp. 042318.

[9] Aanesland A., Charles C., Boswell R. W., Lieberman M. A., “Grounded radio-frequency electrodes in contact with high density plasmas”, *Physics of Plasmas* Vol. 12, No. 10, 2005, pp. 103505.