Electric propulsion using ion-ion plasmas

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Abstract. Recently, we have proposed to use both positive and negative ions for thrust in an electromagnetic space propulsion system. This concept is called PEGASES for Plasma Propulsion with Electronegative GASES and has been patented by the Ecole Polytechnique in France in 2007. The basic idea is to create a stratified plasma with an electron free (ion-ion plasma) region at the periphery of a highly ionized plasma core such that both positive and negative ions can be extracted and accelerated to provide thrust. As the extracted beam is globally neutral there is no need for a downstream neutralizer. The recombination of positive and negative ions is very efficient and will result in a fast recombination downstream of the thruster and hence there is no creation of a plasma plume downstream. The first PEGASES prototype, designed in 2007, has recently been installed in a small vacuum chamber for preliminary tests in our laboratory and the first results have been presented in several conferences. This paper reviews important work that has been used in the process of designing the first PEGASES prototype.

1. Introduction
The scientific history of space propulsion and space exploration can we traced back to the early 20th century, and was mainly driven by three pioneers Robert H. Goddard, Konstantin E. Tsiolkovskiy and Hermann J. Oberth. Their theoretical works also included suggestions on actual space propulsion concepts, and some of them have laid out many of the principles of modern space flights [1, 2, 3]. For example, any method to propel a spacecraft, space vehicle or rocket works on the same basic principle, namely to create thrust by accelerating and expelling mass. The rocket equation based on the conservation of momentum, was derived by Tsiolkovskiy and first published in 1903. This equation is still one of the most important equation for space scientist today,

\[ \Delta v = v_e \ln \left( \frac{m_i}{m_f} \right), \]

and it shows that the velocity change, \( \Delta v \), is determined by the exhaust velocity of the propellant, \( v_e \), and the logarithm of the mass ratio between the initial and final mass of the space craft, \( m_i \) and \( m_f \), respectively. The thrust, \( T \), is given by

\[ T = v_e \frac{dm}{dt}, \]

where \( m \) is the mass of the ejected propellant. Chemical rockets obtain a large thrust by expelling a lot of mass very quickly, and achieve thrust values in the order of \( 10^3 - 10^7 \) N. This high thrust
is needed to overcome earth’s gravitation and escape into space. However, the exhaust velocity of chemical rockets is low, only in the order of a few km/s, so this method is very fuel or propellant consuming. The challenge for any kind of space missions (this being everything from satellites in orbit to long inter-stellar explorations) is in general to make the mission as cost effective as possible. One “efficient” way is to reduce the propellant burden and hence the mass of the spacecraft. Equation 1 shows that to use less propellant requires higher exhaust velocities, which is the key limitation of chemical rockets. In this respect, electric propulsion is promising and has become more and more popular in recent years. The exhaust velocity of electric propulsion systems is high and can reach up to 100 km/s for heavy propellant such as Xenon atoms. This means a significant reduction in the propellant burden: Electric propulsion systems use only 1/10th of the fuel used in chemical rockets. The thrust given by electric propulsion is relatively low (so they can not be used to leave earth), however, they provide the large velocity change ($\Delta v$) needed for long interplanetary missions.

The two main existing thrusters, already used on space missions, are gridded thrusters (also called ion engines) and Hall effect thrusters (also called closed drift thrusters)[3, 4, 5, and references therein]. In these classical electrostatic and electromagnetic thrusters (illustrated in Figure 1(a), the thrust is provided solely by extracting and accelerating positive ions. To avoid a built up of negative charge on the space vessel that will counteract the accelerating field, a flow of electrons is added to the positive ion beam downstream of the acceleration stage. These electrons are fed from a hollow cathode. To a large extent, the properties of the cathode material, it’s physical configuration and the structure of the cathode plasma determine the performance and life of both ion and Hall thrusters [3]. The neutralizer is therefore very important in the present technologies and huge efforts are made to increase their performance and lifetime, but also efforts are put in to develop new concepts where the neutralizer is not needed.

The recombination between ions and electrons is a rather slow process and the presence of electrons downstream adds to the ionization in this region. Hence, even if charge neutrality is insured a downstream plasma with charged particles exists outside of the thruster body, this plasma is known as the plasma plume. The possible damage the plume may cause on the host spacecraft is the main reason why it has been and is still a great concern in using electric propulsion systems to propel a spacecraft rather than using conventional chemical propulsion [6]. One of the major problems with the plasma plume is that the accelerated ions might undergo charge exchange collisions with the slow neutrals, which then produces slow ions that can backscatter and deposit on the thruster body, solar panels, scientific instruments, etc. In the early 1970s a “Porcupine” rocket project was launched to investigate the behavior of an artificial ion beam in the Ionosphere. The results showed that the Xenon ion beam induced high-frequency turbulence as far away as 100 m from the thruster [7, 8]. High and low frequency oscillations in both current and space potential can occur due to the cathode plume interacting with the thruster plume. These oscillations increase the erosion of grids and walls and again limits the lifetime and performance of the thrusters [3, and references therein].

New electric propulsion systems are now intensively studied in order to prolong the lifetime and performances of electrostatic and electromagnetic thrusters. Some of them does not need a neutralizer [9].

1.1. Ion-ion plasma for electric propulsion

Using ion-ion plasma in order to accelerate both positive and negative ions for thrust is a new concept for electric propulsion. By creating a stratified high density plasma with an ion-ion plasma at the periphery allows to extract and accelerate both positive and negative ion beams for thrust. In this way there is no need for a downstream neutralizer and as no electrons are present in the extractors nor downstream of the acceleration stage, there is no downstream plasma plume. The concept was patented by the Ecole Polytechnique early 2007 [10] and is
Figure 1. a) Illustration of electropositive plasma thrusters such as the Hall thruster and the gridded ion engine, where a positive xenon beam is neutralized by electrons downstream of the acceleration stage. b) Illustration of the electronegative plasma thruster concept, where both positive and negative ions are accelerated from an electron free region (ion-ion plasma).

called PEGASES for plasma propulsion with electronegative gases. The first prototype was installed in a small vacuum chamber for preliminary tests in our laboratory late 2007 and the first results have been presented at several conferences [11]. A simplified illustration of the system is shown in Figure 1(b). There are many scientific and technological issues that have to be addressed before this concept can be developed into an operating plasma propulsion system in space, and for clarity they can be divided into three stages:

Stage 1) The ionization stage with an electronegative propellant,
Stage 2) Ion-ion plasma formation,
Stage 3) Positive and negative ion acceleration.

Following this introduction on some of the space propulsion challenges this paper will review important experimental, simulation and theoretical works that have come to the design of the first ion-ion plasma thruster prototype. These works are mainly focused on strong electronegative plasmas and in particular on ion-ion plasmas. Section II discusses the ionization stage and the use of electronegative gases, section III the ion-ion formation and section IV the challenges on accelerating both positive and negative ions, and finally a conclusion with the description of the first PEGASES design is given in section V.
2. Stage 1, Ionization stage

2.1. The electronegative propellant

The propellant or fuel has to be an electronegative gas in order to produce both positive and negative ions. The best propellant is presumably iodine, $I_2$, which is heavy (good for high thrust) and very electronegative and therefore will efficiently produce negative ions. The attachment cross section is maximum and very high at zero (electron) energy. In addition, the ionization thresholds are low, about 9.41 eV for $I_2$ and 10.5 eV for $I$, fairly easily leading to fully ionized plasma core at moderate rf power. Iodine is in solid state at room temperature, but with a large vapor pressure, which allows small and light conditioning tanks. Finally, it is inexpensive.

Already in the 1930s and 40s iodine plasmas were known to produce strong electronegative plasmas, and they were therefore used to study the plasma dynamics influenced by negative ions. The works performed during this period has been reviewed in the book by Emelens and Woolsey [12]. In the 1970’s halogen ion sources were investigated as negative ion sources in fusion reactors [13]. Bacal and Doucet [14, 15] obtained what they called electronegative ion-rich plasmas with electronegative ion densities of 90% of the positive ion densities in iodine plasmas. The negative ion densities in iodine was much higher than what was obtained in Oxygen under similar conditions. They found that the upper limit of the electronegative density in their system was limited by the required presence of electrons to ensure an electrostatic confinement of the ion-ion plasma by the ambipolar diffusion of positive ions and electrons.

Recently, iodine has been proposed as a lower cost propellant alternative for ion and hall effect thrusters [16]. The reason for suggesting iodine is based on the same arguments as given above (the low ionization potential of both $I_2$ and $I$, the high atomic mass of $I$, as well as the weight savings associated with the storing a solid fuel with low vapor pressure), but its ability to create negative ions was not considered here. As pointed out by both Dressler et al and Tverdokhelbov et al [16, 17] an important disadvantage of using Iodine is its corrosiveness. There are therefore currently no active development efforts on iodine propellant for electropositive thrusters [18]. However, given the substantially more corrosive chemical thruster fuels such as hydrazine and ammonia, it is not evident that the corrosiveness of iodine will prevent the use if iodine in space.

Not to forget, in space there is no need for sophisticated and fragile vacuum pumps, as in the laboratory, so the corrosiveness and contamination of iodine is therefore not of a great concern when used in space. But for preliminary tests in the laboratory it would be some extra expenses to have high quality vacuum for iodine experiments, and tests should therefore first be made in $Cl_2$ as suggested by Grisham [19, 13]. Nevertheless, any electronegative gas can be used as propellant.

2.2. Efficiency of ion-ion plasmas

Electronegative gases are molecular gases where energy goes into dissociation and change of vibrational states in addition to ionization and attachment. Hence, creating both positive and negative ions costs more in electrical power than creating only positive ions, although the electrons undergoing attachment collisions have already been created by the electron-positive-ion pair. The recombination between positive and negative ions is very efficient, resulting typically in a lower ion densities in ion-ion plasmas than in electropositive plasmas. One of the big challenges for plasma propulsion with ion-ion plasmas lays therefore in creating high density ion-ion plasmas.

3. Stage 2, Ion-Ion plasma formation

3.1. Ion-ion plasmas

Ion-ion plasmas are electron-free plasmas that consist of positive and negative ions, only (in addition to the neutral particles). In other words, the plasmas dynamics of the negatively charged particles is dominated by heavy “stationary” negative ions rather than by light and
mobile electrons. Such plasmas, with only heavy stationary charged particles, are significantly different from the more common electropositive and weakly electronegative plasmas. Ion-ion plasmas have been investigated both experimentally and theoretically (see the following references below), but not to a great extent and there are many remaining physical properties to be explored in this field of plasma physics. Ion-ion plasmas may be formed in the afterglow of pulsed electronegative plasmas, in electron beam generated plasmas and in the periphery of magnetically confined electronegative plasmas (we will come back to this later).

Electronegative plasmas operated in a continuous mode often consist of a core, where negative ions accumulate, surrounded by an electropositive region, with only positive ions and electrons, in front of the positive ion sheath close to the wall. This stratification of electronegative plasmas is due to the trapping of negative ions by the ambipolar electric field set up by the mobile electrons. Thus in this situation the negative ion flux to the wall is essentially zero. Operating the plasma in a pulsed mode destroys this stratified structure in the afterglow and allows the formation of an ion-ion plasma near the wall [20]. Ahn et al and Malyshev et al [21, 22] recognized that pulsed electronegative discharges can ameliorate anomalous etch profiles, such as notching and other forms of charging damage that occurs in conventional continuous wave discharges, due to the access of the negative ions at the wall. Figure 2 shows a 1D fluid simulation of the temporal evolution of densities, temperatures and ion fluxes to a non biased substrate, in a pulsed chlorine discharge by Midha and Economou [23, 24]. When the power is switched off the electrons respond to the fastest time scale (0.1 µs), electrons are thermalized and their temperature drops very quickly. This temperature drop is then followed by a rapid drop in the electron density and an increase in the negative ion density. The ion-ion plasma is formed on a longer timescale in the order of 10 µs where the ions can react.

For a plasma propulsion system, the ion-ion plasma formed in the afterglow of a pulsed plasma would not be very efficient as the densities drop significantly, as can be seen from figure 2. Pulsing the plasma also add one more element that can fail and makes the system heavier and bigger. Hence, for an electronegative ion thruster a continuous operation is better, but access to the negative ions in the acceleration stage is needed (in contrast to the above continuous
situation).

Walton et al [25, 26] produce large negative ion densities in continuously operated electron-beam-generated plasmas. In these plasmas the electron temperature is very low ($T_e < 1.0 \text{ eV}$), hence the electron attachment rate is high and becomes comparable to the ionization rate. Figures 3 and 4 show, respectively, the attachment and ionization rates for SF$_6$ and Cl$_2$ as a function of electron temperature (cross sections integrated over a Maxwellian distribution of electrons). It can be seen that below 1-2 eV the attachment rate becomes comparable and even dominant over the ionization rate. In this case most electrons created are converted to negative ions, hence forming an ion-ion plasma. We will come back to the work by Walton et al in section IV, where we discuss the extraction and acceleration of positive and negative ion beams. Producing an ion-ion plasma by electron beams is very efficient, however, the electron beam is fed from a hollow cathode. As we saw in the introduction the hollow cathode has a limited lifetime and we try to get rid of them in space propulsion systems.

3.2. Electron filtering by magnetic fields

Another way to produce an ion-ion plasma region, where the ions are accessible for acceleration, is by using moderate static magnetic fields to confine the electrons along the field lines but allow the ions to move perpendicular to the field, i.e. electron filtering. For example, Walton et al [25, 26] use a magnetic fields of the order of 100 - 200 Gauss to collimate the electron beam, while Kawai et al [27] use a magnetic fields of the order of 2 kG which confines also the ions in a beam generated plasma. In both of these configurations ion-ion plasmas are achieved in the active phase of operation in both Ar/SF$_6$ mixtures and CF$_4$ with ion densities (in the ion-ion region) in the range of $10^9$ cm$^{-3}$. Amemiya et al [28] produces an almost electron-free region in a target chamber separated from the source chamber by a magnetic filter consisting of an array of permanent magnets. The source plasma was in this case a capacitively coupled oxygen plasma with a source plasma density of $10^9 - 10^{10}$ cm$^{-3}$ and a target ion-ion plasma density of $10^8 - 10^9$ cm$^{-3}$. Grisham et al [29, 19, 13] generate negative ion beams from a magnetic cusp-confined rf-driven volume production source. The driver plasma is separated from the extractor plane by a pair of permanent magnets with a filter field of around 300 Gcm and a peak value of about 180 G. An ion-ion plasma forms the extractor region between the magnetic filter and
Figure 5. A schematic of the Helicon source at LPTP (Ecole Polytechnique), indicating the plasma core (weakly electronegative plasma), the transition layer and the ion-ion plasma region.

the grids, where the extracted negative ion current (Cl\textsuperscript{−}) is 85-90 % of the positive ion current (Cl\textsuperscript{+} and Cl\textsubscript{2}\textsuperscript{+}). Considering the position of their diagnostic probe it is likely that the negative ions undergo more loss due to stripping reactions than the positive ions suffer due to charge exchange. The negative ion current density extracted from this source is 12 mA/cm\textsuperscript{2} at 30 kV extraction and 15 kW rf.

At the Ecole Polytechnique, we have been studying the stratification of electronegative plasmas due to the magnetic filtering in a helicon source operating in SF\textsubscript{6} and mixtures of SF\textsubscript{6} and argon [30, 31, 32, 11]. These works have led to the design of the first PEGASES prototype, and we will now briefly review these results.

A schematic of this Helicon experiment is shown in Figure 5. The negative ion fraction was characterized using an electrostatic two-probe method [30] and by photodetachment [32]. Figure 6 shows a stratified plasma with: 1) A plasma core where the source electrons are confined by the axial magnetic field and where the plasma potential is greatest. 2) A transition layer with a potential drop of several volts and 3) an ion-ion region near the walls, where the electrons can be neglected. Figure 7 shows Langmuir probe characteristics obtained in the plasma edge/ion-ion region for different radial positions. At \( r = 13 \) cm the current collected by the probe biased positively is very large compared to the positive ion current collected when the probe is biased negatively. This is due to the presence of hot electrons in addition to negative ions. As the probe is moved towards the edge/radial wall the characteristic becomes symmetrical with almost equal positive and the negative currents (the difference being mainly a result of the mass difference between the positive and negative ions). Here the negative current is dominated by
Figure 6. Radial profile of plasma potential (a) and negative ion fraction (b) in the diffusion chamber of the helicon reactor for pure SF6 plasma operating at 400 W rf power. Figures taken from Chabert et al [30].

Figure 7. Langmuir probe characteristics for different radial positions in the edge region of the Helicon diffusion chamber operating with a mixture of Ar and SF6 (1:1) at 0.13 Pa (1 mTorr), 600 W rf power and a magnetic field of about 100 G. Figure taken from N. Plihon [32, PhD thesis at Ecole Polytechnique], and a similar figure is published in Corr et al [31].

cold negative ions, and shows that electrons have been filtered by the magnetic field. The edge plasma is electron-free and is only composed of positive and negative ions. It was shown that operating the helicon source in inductive mode without a magnetic field creates a highly unstable electronegative plasma in the whole region of the diffusion chamber Corr et al [31]. When the magnetic field increases a transition occurs from the unstable electrostatic confinement to a magnetic confinement where the plasma becomes stable and the stratification showed above occurs. Figure 8 shows the ratio of the negative ion fraction in the centre and at the edge of the diffusion chamber as a function of the magnetic field, indicating a strong stratification at higher magnetic fields. The ion densities in the ion-ion region is, also here, about $10^9 \text{ cm}^{-3}$. Figure 7(b) shows that the ion densities drop rapidly by more than 50% within 1-2 cm. The challenge
for efficient utilization of ion-ion plasmas for space propulsion as well as for the etching industry and fusion applications is to be able to increase the ion densities in the ion-ion plasma region.

3.3. Magnetic electron filtering: modeling and simulation
The formation of ion-ion plasmas or highly electronegative plasmas has been investigated by analytical and numerical modeling. The focus has mainly been on the spatio-temporal evolution of pulsed electronegative discharges [33, 34, 23, 20, and references therein]. The formation of ion-ion plasmas by electron magnetic filtering has been very little investigated. Franklin and Snell [35] modeled the positive column with negative ions in a magnetic field. They examined a low pressure plasma (in the mTorr range) where electrons are essentially confined along the field lines in the center of the discharge while ions are not and can move perpendicular to the field. They assumed that the negative ion flux was zero at the boundary wall and that the system was infinitely long along the magnetic field lines. Under these conditions, they obtained solutions with an ion-ion plasma at the periphery. These assumptions do not fit the experimental conditions for the PEGASES electronegative plasma thruster where the system is bounded in the parallel direction and the negative and positive ion fluxes out of the system is finite.

We have recently developed a two-dimensional magnetized plasma fluid simulation to investigate the electron magnetic filtering in electronegative plasmas [36]. The model uses the three first moments of the Boltzmann equation, namely the continuity equation, the conservation of momentum approximated by the drift-diffusion equation and an energy equation for the electrons. The various reaction rates, mobility and diffusion constants (accounting for the presence of an axial magnetic field) are calculated from experimental cross-sections by using a Boltzmann solver. The model is simulating an oxygen plasma following the various species O$_2$, O, O$_3^+$, O$^-$ and 14 reactions between them are taken into account (momentum transfer, dissociative attachment, dissociation, ionization, electron impact detachment, dissociative recombination, mutual neutralization etc.). The magnetic field is uniform and parallel to the system axis. Figure 9 shows results obtained with a 30 cm long and 20 cm diameter grounded cylinder.
where the neutral pressure was 5 mTorr and the inductive power was 50 W with a heating profile maximum on the axis of the cylinder and exponentially decaying from the center of the discharge.

Figure 9(a) shows the radial negative ion fraction $\alpha = n_−/n_e$ for three different magnetic fields and confirms that for low or null magnetic field, the plasma presents the usual stratified structure with an electronegative core ($\alpha$ large) and an electropositive periphery ($\alpha$ almost null), while for a sufficiently large magnetic field strength, the plasma appears to be electronegative along the whole radius. In addition, for $r > 12$ cm the negative ion density becomes several orders of magnitude larger than that of the electrons, hence forming an ion-ion plasma at the periphery of the discharge. Figure 9(b) shows the neutral, ion and electron densities as a function of radius for the 500 G case. The electron density is high in the inductive heating area decreasing rapidly by several orders of magnitude around 5 cm. At this position, the negative ion fraction increases and the negative ion density becomes of the order of the positive ion density ($O_2^+$). At a radius $r > 10$ cm the ion-ion plasma is formed with an ion density of the order of $10^9$ cm$^{-3}$.

The simulation has been validated for known parameters and will be used to investigate the large parameter space in order to make the ion-ion source as efficient as possible.

4. Extraction and acceleration stage

The sheath, the pre-sheath and their formation are fundamental features in the design of extraction grids for ion beam generation. Due to the lower temperature and greater mass of negative ions compared to electrons, the sheath structure in ion-ion plasmas differs significantly from that of conventional electron-ion plasmas. For the case of the PEGASES prototype we envisage two methods for ion extraction and acceleration via grids. The first is to have two separate, but neighboring grids, one biased negatively to extract a positive beam and one biased positively to extract a negative beam. The second method is to use one grid alternately biased positively and negatively.

Kanakasabapathy et al [37, 38] and Walton et al [25, 26] have shown that comparable fluxes of positive and negative ions can be extracted from an ion-ion plasma using a low-frequency sinusoidal bias. Kanakasabapathy et al extracted ion beams from an ion-ion plasma formed in the afterglow of pulsed plasmas, while Walton et al extracted both ion species during the active phase of a pulsed plasma. Midha, Economou and coworkers [39, 40] developed a time-dependent
fluid model to investigate the dynamics of an ion-ion plasma under the influence of a rf and a dc voltage and found that the sheath structure differed significantly from conventional electron-ion plasmas. When the biased frequency is varied the sheath region shows profound structure changes, where the response of the ion-ion plasma to an rf bias depends on the characteristic time scale for collisions and the ion plasma frequency. To effectively extract positive and negative beams with very high velocities using one biased grid therefore require an optimization of both the frequency and the waveform. We have investigated the size of the sheath and the existence of a pre-sheath via a particle-in-cell simulation [41]. We found that Child-law type sheaths forms in ion-ion plasmas under the influence of a dc bias, but the size is controlled by the reflected ion species rather than by that of the electrons. The sheath formation is within a few microseconds which corresponds to the ion transit time. In addition, there exists the equivalent of a Bohm criterion in ion-ion plasmas (as for classical ion-electron plasmas) where the electron temperature is replaced by the temperature of the ion reflected by the sheath. Figure 10 shows the sheath width $s$ as a function of $V_0^{3/4}$ (black dots). This width is well fitted by a straight line (dashed line) which slope is very close (within 5%) to the theoretical high voltage sheath using the corresponding ion temperature. The dotted-dashed line shows the theoretical sheath width if ions were entering the sheath with a thermal velocity rather than with the sound speed (i.e. if there were no presheath). The consequence of this finding is twofold: the ion velocity at the entrance of the sheath of an ion-ion plasma is larger than the average velocity along one direction of a thermal distribution and, consequently, the sheath size is smaller, which, for the design of acceleration grids, is crucial.

We also observed that even a slight difference in the positive and negative masses (as small as 5%) yields a strong asymmetric potential, where the bulk potential sits much closer to one of the electrodes, hence, getting closer to a conventional electron-ion plasma. This issue needs to be fully understood if molecular gases such as O$_2$ and SF$_6$, which forms ions of different masses, are used as propellant in the electronegative thruster.
5. Conclusion

The PEGASES thruster (Plasma propulsion with Electronegative GASES) is a new concept of plasma propulsion where both positive and negative ions are used for thrust. In this way there is no need for a downstream neutralization by electrons. A downstream plasma plume is presumably avoided due to the absence of downstream electrons and the efficient recombination of positive and negative ions (compared to ion electron recombination).

In this paper we have reviewed the works that have lead to the design of the first PEGASES prototype, where the use of electronegative gases, the formation of an ion-ion plasma and extraction and acceleration of ion beams have been discussed.

To conclude, the first PEGASES prototype is shown on figure 11(a) and the schematic of the prototype is shown in Figure 11(b). Note that in this photo PEGASES is operating in Argon (which is not an electronegative gas) for mass efficiency tests and calibration of diagnostics.

The main plasma is produced in a long cylinder, 20 cm long and 4 cm in diameter. Four solenoids create a longitudinal magnetic field of moderate magnitude. Typically 100-200 Gauss is obtained with dc currents of 1-3 Amperes. This field confines the electrons but not the ions. The plasma is generated by a three loop radio frequency (13.56 MHz) antenna coupled to the plasma either in inductive or helicon mode. 50 W to 2 kW rf power is used. As the thruster is immersed completely into the vacuum chamber, the plasma is pulsed above 400 W to avoid overheating. The ion-ion plasma is formed in the two extractors, and will be accelerated via biased grids. These grids are not yet installed. Preliminary results using SF$_6$ and O$_2$ as a propellant indicates a strong electronegative plasma in the extractors, with a negative ion fraction ($\alpha = n_- / n_e$) of 30 in SF$_6$ and 20 in O$_2$ under similar conditions. Results from the prototype will be published in the near future.

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