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# Inductively coupled electronegative plasmas applied to space propulsion

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Low-pressure electronegative plasmas are typically stratified plasmas with the negative ions accumulated in the centre of the discharge due to the ambipolar electric field. The negative ions can therefore not reach the surrounding boundaries and their flux to the wall is negligible. The situation change when pulsing the plasma or applying a magnetic field: in the fist case the electrons are lost rapidly in the early afterglow leaving behind an ion-ion plasma that decays within the diffusion time of the ions. In the latter case, the electrons are confined in the centre of the discharge by the magnetic field, and allow under certain conditions the formation of an ion-ion plasma at the plasma periphery close to the boundaries. Due to the reduced number of electrons in the ion-ion region, the ambipolar field is weak or vanishing and both the positively and the negatively charged ions can reach the wall. This particular plasma state can therefore be used as a dual positive-negative ion source and finds applications in for example the semiconductor industry for charge-free etching [1-3], neutral beam injection for fusion [4] or for space propulsion [5,6].

The PEGASES thruster (Plasma propulsion with Electronegative GASES) is a new concept for space propulsion where the aim is to accelerate both positive and negative ions to provide the thrust for the spacecraft. The concept and the first prototype has been described in detail previously [6,7], and relies on the formation of a *high-density* ion-ion plasma in the region of ion extraction and on the ability to extract and accelerate oppositely charged ions form the same source. In this paper we will present the recent results on the ion-ion plasma formation in magnetized plasmas, the preliminary investigation of the ion acceleration (a technology that is not yet fully developed) and a discussion on possible improvements of the design.

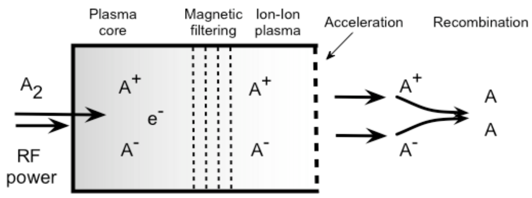


**Figure 1** Illustration of the PEGASES trhuster

The stratification of the electronegative plasmas due to a magnetic field has been studied experimentally and analytically in cylindrical geometries where the magnetic field is parallel to the cylinder axis [6-9]. It was shown that in moderate magnetic fields of 200 G, strong electronegative plasmas formed at the periphery of a 3 cm radius cylinder. However, the ion-ion plasma condition was reached only when the magnetic field was increased to about 1000 G in the same geometry. (The parameter space between 200 and 1000 G could not be investigated experimentally as additional permanent magnets were used to increase the magnetic field strength). In a space propulsion application, it is desirable to reduce the strength of the applied magnetic field in order to reduce the load of the magnetic unit and also to avoid *a magnetic connection* with the rest of the spacecraft. A new method to improve the formation of an ion-ion plasma exploiting the moderate magnetic field (200 G) together with a tailored gas injection is therefore investigated. The magnetic field reduces the perpendicular electron mobility and results in a decreasing electron temperature perpendicular to the field. As the ionization and attachment rates are strongly dependent on the electron temperatures and dominate respectively at high and low *Te*, the positive ions are created in the core of the plasma, where the heating takes place, while the negative ions are created at the periphery. Introducing the neutral gas in the low temperature region (in addition to the injection in the core) can increase the production of negative ions, and it is shown that an ion-ion plasma forms with optimal gas flows in the two regions. The physics and optimization of this technique is currently being explored and will be presented here.

The acceleration of positive ions out of the PEGASES thruster has been investigated in the case of electropositive plasmas. An illustration of the experimental setup is shown on figure 2. The quartz cylinder, in which the plasma is confined by the magnetic field, is terminated by metallic endplates that can be biased to positive potentials $V_0$. As the plasma conductivity perpendicular to the field is reduced, we expect that the plasma will float on top of the applied potential to $V_p+V_0$, where $V_p$ is the plasma potential [10]. The thruster is immersed in a large grounded vacuum chamber and the only connection to ground is through the extractors, allowing an electric field to exist between the plasma core and the grounded vacuum chamber. Preliminary experiments have shown that with this configuration the ion flux out of the extractors increases and a visible plasma plum is observed. How the electric field is distributed along the extractor and if ions are accelerated by this field will be investigated.

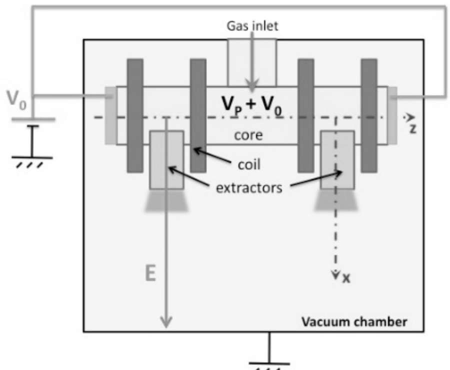


**Figure 2** Illustration of the PEGASES experimental seutp with biased endplates.

As illustrated in figure 2, first prototype has two extractors with the extraction surface perpendicular to the cylinder axis and the magnetic field. The two extractors were originally intended for separate extraction of positive and negative ions. One issue with this method is that the accelerated ions have to be brought back to the same potential before being able to recombine. Since the ions originate from the same source the effective acceleration potential will become zero and no net thrust can possibly be achieved [11]. There are, in addition, some minor technological issues with the first design, such as small extractor areas compared to the thruster body, non-uniform plasma with one extractor brighter than the other, difficulty in up-scaling etc. In collaboration with V. Godyak, a new prototype is being designed with an inductively coupled antenna at 4 MHz and only one extractor surface, allowing alternate extraction and acceleration of positively and negatively charged ions.

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