Investigation of Ion-Ion Plasmas for Application in Electric Thrusters.

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Abstract: While conducting experiments for the ion-ion plasma based PEGASES thruster in a basic magnetized RF discharge we encountered a strip like structure in the region of the magnetic barrier. After examining the origin of the strip with a series of experiments, the most likely explanation for this strip is an ExB drift in the plasma. The E-field originates in a capacitive coupling of our antenna to the plasma which is directly avoided in the PEGASES prototype but not in our discharge tube. To prevent the strip and create more similar conditions to the PEGASES prototype, a Faraday shield was placed between the antenna and the discharge tube. This shield localizes the electrostatic field between the antenna and the tube and leads to an inductive coupling of the plasma. With this setup an ion-ion plasma in a SF_6/Ar mixture has been observed.

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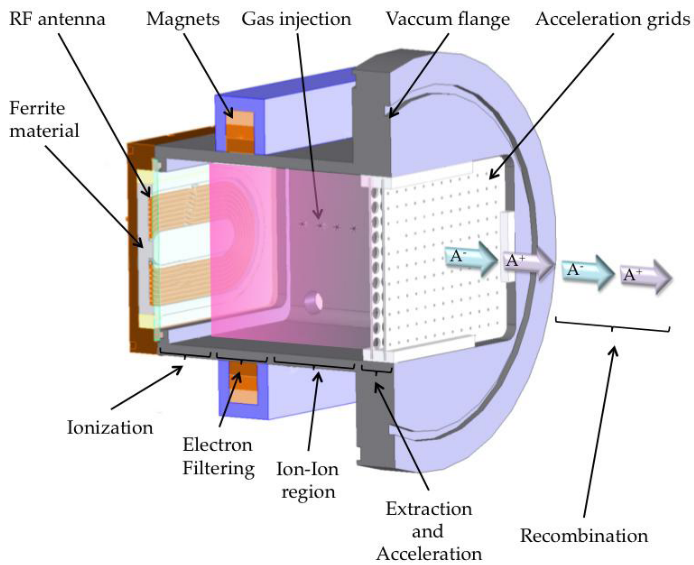

Figure 1. 3D Model of the second PEGASES prototype.

I. Introduction

Nowadays, the constantly growing market of electric space propulsion is dominated by two types of thrusters, the gridded ion engine and the Hall effect thruster. Still, a further technological development of both thruster types is restrained due to several limitations, like a need for a neutralizing cathode, a critical component which can limit the reliability of propulsion device, as well as the possibility for the spacecraft elements, e.g. solar arrays and optical equipment, to be damaged by ions backscattered from the plasma plume.

In 2007 Pascal Chabert patented a new concept of electric thruster called PEGASES (Plasma propulsion with Electronegative GASES)[1–3]. It is based on creation and acceleration of an ion-ion plasma. A 3D-image of the second version of the PEGASES prototype is shown in Fig. 1. It is currently mounted on a test bench in the LPP laboratory at the Ecole Polytechnique in Paris. Initially, a radio frequency (RF) electronegative plasma is generated by exciting and ionizing an electronegative gas, like O_2 or SF_6, using a RF antenna. In addition to electrons, positive ions and neutrals, an electronegative plasma also contains negative ions. Electrons of this electronegative plasma are then filtered out by means of a magnetic barrier. Furthermore, the electrons captured by the magnetic field are cooled down to a temperature where they can more easily attach to neutral atoms or molecules, thus creating more negative ions. An electron-free, electronegative plasma, containing only positive and negative ions as charge carriers, is called an ion-ion plasma.

The magnetic filtering stage represents a complicated technological challenge. It has to be strong enough to filter out and to cool down the electrons so that they can attach to the neutral atoms or molecules, without influencing and perturbing the ions. A magnetic field perpendicular to the plasma flow has been shown to be the most promising approach.

The ion-ion plasma is accelerated using a set of polarized grids in order to create thrust[4]. The acceleration stage in the PEGASES thruster is comparable to the classical gridded ion thrusters design. The main difference is that the grid is biased with an alternating voltage to allow for the positive and negative ions to be accelerated separately.

Due to the fact that in this thruster both positive and negative ions are accelerated, there is no need for a neutralizing cathode. In addition, the recombination of positive and negative ions is more efficient than that of electrons and positive ions. This reduces the recombination length in the plume. Thus, a degradation and possible contamination of the spacecraft, especially the solar panels and the optical equipment, due to backscattering of the ions can be minimized.

Ion-ion plasmas are still insufficiently explored. The absence of electrons, as well as comparable masses and energies of the positively- and negatively-charged species make the behavior and characteristics of such

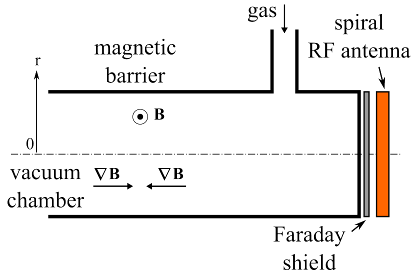

Figure 2. Drawing of the simple discharge tube for experiments with the magnetic field.

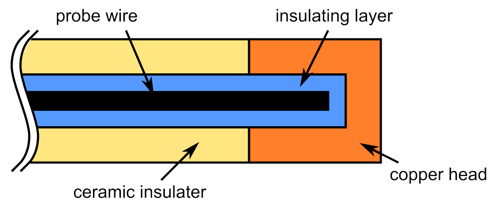

Figure 3. RF fluctuation probe to measure the change in the plasma potential induced by the RF.

plasmas significantly different from the ones of the well-known electropositive plasmas[5]. New studies are necessary in order to provide a better understanding of the ion-ion plasmas.

II. Experimental Setup

In order to perform detailed studies on the physics of ion-ion plasmas, a more basic discharge tube, shown in Fig. 2, has been constructed at the institute ICARE of the CNRS in Orléans. A flat-end quartz tube is mounted on a vacuum chamber. The gas is introduced through the side-injection gas feed. A flat RF antenna, operating at the RF frequency of 13.56 MHz, is positioned at the tube end. This discharge tube allows us a full visual access and a possibility of fast set-up modifications in order to conduct a variety of experiments using different parameters and different configurations. Two power supplies are available, a RF generator with a power range from 5 W to 1000 W and a fixed frequency of 13.56 MHz and a RF amplifier which can amplify different waveforms, generated by a signal generator, in the frequency range from 10 MHz to 100 MHz with a maximum power of 200 W. To get the power to the antenna an have it not just reflected a L-type matchbox is used to tune the circuit to the maximum power output.

The experiments have been performed in the EPIC (Electric Propulsion Innovative Concepts) test bench, see Fig. 4, of the ICARE laboratory at the CNRS Orléans. The vacuum chamber has a diameter of 0.4 m and a length of 0.75 m and is equipped with a 350 l (in nitrogen) turbomolecular pump which is connected to a primary vacuum pump to reach an optimal pumping speed. EPIC has a variety of optical windows and electrical passthroughs so it can be equipped with a variety of probes and linear motion stages. A pressure down to 10^{-7} mbar can be reached without a gas flow. The typical working pressure at gas flow rates from 1 sccm to 100 sccm is typically arround 10^{-4} mbar to 10^{-2} mbar depending on the gas.

A Langmuir probe has been used to measure the plasma parameters. The probe has been outfitted with chokes which have a resonance frequency of 13.56 MHz and 27.12 MHz to compensate for the RF induced changes in the plasma. Although the Langmuir probe is frequently used for characterizing classical plasmas, only few experiments have been done in electronegative plasmas[5]. However, when it comes to measuring the plasma parameters within the magnetic field, the Langmuir probe is not well understood, as the theory needs to be adapted. In this case, a floating emissive probe has been used to determine the plasma potential.

In order to measure the change in the plasma potential a RF fluctuations probe (Fig. 3) has been used. This probe consist of an isolated wire which is inserted into a copper cylinder. There is no electrical contact between the wire and the cylinder. This probe works like a capacitor and measures the fluctuations in the plasma without draining the region of its charges. This allows a more precise measurement than with just with a wire probe in the plasma, which would underestimate the RF fluctuations. A calibration has to be made to calculate the factor between the voltage measured on the probe wire an the voltage applied to the head.

A planar probe has been used to measure the ion current in the plasma. The probe consist of an cylinder, with a diameter of 4 mm, which is biased with a voltage of -60 V, to attract the positive ions. By measuring the average current, to compensate for the RF fluctuations, flowing through this probe we have directly the ion current.

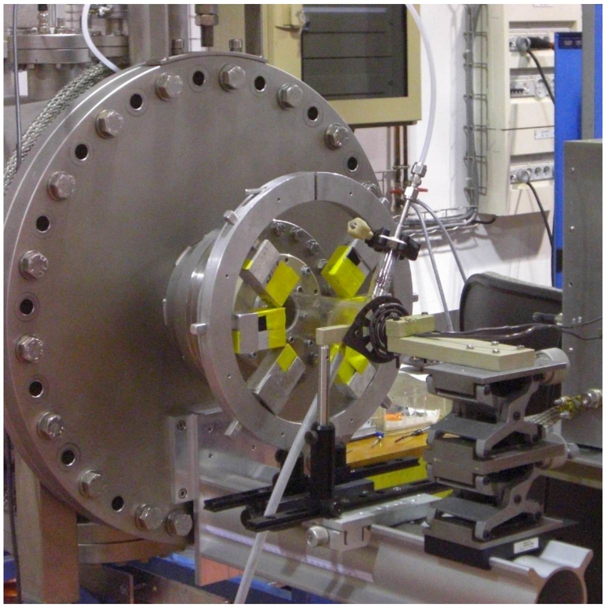

Figure 4. Foto of the EPIC test chamber in the ICARE lab at the CNRS Orléans with the RF antenna, the discharge tube and the magnetic barrier.

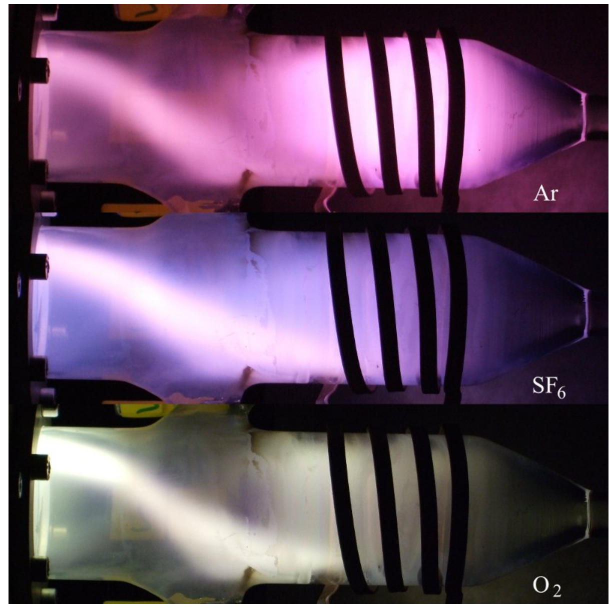

Figure 5. Side view of the strip-like structure in argon, SF_6 and oxygen (20 sccm gasflow, 500 G magnetic field on-axis and 250 W input power) generated by a spiral antenna with the gas feed on the tube axis.

III. Results and Discussion

In these experiments, the formation of a stationary two-dimensional strip instability has been observed in the region of high magnetic field strength for different types of gases and B-field strength (see Fig. 5).

The strip structure has been observed over a broad range of parameters. The original electronegative gas SF_6, has been changed to Ar since it is a commonly used gas and has well documented properties. But even experiments in Xe, He, O_2 and N_2 did not change the appearance of the strip[6]. From that we conclude that the strip formation is not connected to the electronegativity of the gas. The gas flow rate has been varied between 1 sccm and 120 sccm in Ar, thus varying the pressure between 10^{-4} mbar and 10^{-1} mbar. The RF frequency has been tuned from 10 MHz to 60 MHz and the transmitted power varied between 10 W and 600 W. These changes of the parameters did not seem to have an influence on the formation of the strip and its shape.

However an increment in the inclination of the strip could be observed, by the naked eye, while increasing the strength of the magnetic field from 50 G up to 1200 G (measured at the strongest point on the axis of the discharge tube). We also observed that the direction of the strip changed when we changed the direction of the magnetic field. In all the measurements the inflection point of the strip corresponded to the point where the magnetic field on the axis is strongest.

Measurements carried out with a Langmuir probe at the exit of the tube lead to the assumption that the strip formation serves as a path through the magnetic field, see Fig. 6, and the electrons are not captured but can cross the magnetic field. This inhomogeneity in the plasma reduces the efficiency of the plasma source and makes it difficult to produce a large amount of negative ions.

To measure the plasma density more directly two planar probes were placed in and outside the strip. The probe shows us that the plasma density inside the strip is higher than the density outside the strip. We repeated this experiment after changing the direction of the magnetic field and therefor changing the direction of the strip to compensate for our nonsymmetrical injection, the outcome was the same. This strengthens our assumption that the strip serves as a path through the magnetic field and makes the medium strongly inhomogeneous.

A way of reducing the capacitive coupling is to place a Faraday shield between the antenna and the plasma[7]. The Faraday shield, shown in Fig. 7, will localize the electrostatic field between the antenna and the shield without disturbing the electromagnetic field which drives the plasma.

Placing a shield between the antenna and the discharge tube has indeed a great influence on the plasma.

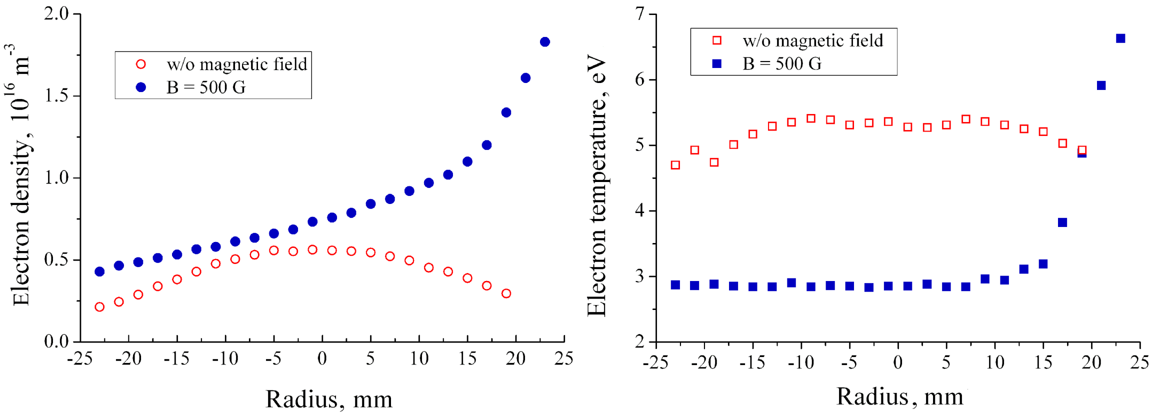

Figure 6. Radial distribution of the plasma density and electron temperature at the exit tube with a magnetic field and strip formation and without a magnetic field in Ar and the strip at the positive end of the r-axis.

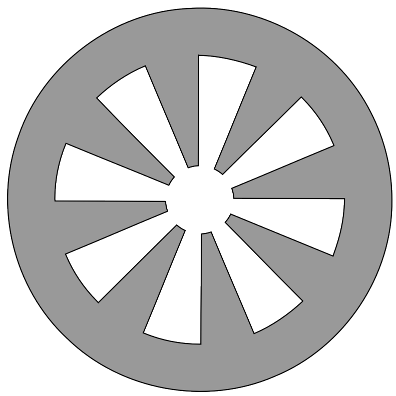

Figure 7. A Faraday shield can be placed between the antenna and the discharge tube to localize the electrostatic field and generate an inductively coupled plasma.

The generation of the plasma now happens in the first few centimeters of the tube and is more luminous than in the case without a shield, which indicates a better power coupling. The plasma does not ignite itself anymore when the RF power is turned on and an igniter needs to be used, although once ignited the plasma can sustain itself. An uncompensated floating Langmuir probe shows that the amplitude of the RF induced plasma oscillation is greatly reduced. These points indicate that we indeed have achieved an inductive coupling.

When placing the magnets around the tube of this plasma, no more strip can be observed (see Fig. 9). The comparison has been made by radial scans with a compensated Langmuir probe at the exit of the tube. With the Faraday shield between the antenna and the tube no radial dependency of the plasma was measured. The same result was obtained with measurements of the planar probe at two radial positions, no radial dependency could be observed after adding the Faraday shield.

The same effect has been observed while doing measurements with an emissive probe along the axis for several conditions. We can see in Fig. 8 that the strip clearly separates the plasma into two zones. The measurement shows us also that the plasma potential is strongly decreased when the Faraday shield is added.

When measuring with a fluctuation probe we could also clearly observe the difference of the amplitude in the RF fluctuations, shown in Fig. 10. The Faraday shield strongly reduces these fluctuations which is an indication for a inductively coupled plasma.

The conducted experiments indicate that the appearance of the strip is due to an $E \times B$ drift, wherein the electric field origins in the capacitive coupling between the antenna and the grounded vacuum chamber.

After introducing the Faraday shield and observing a stripless plasma we switched the gas back to SF_6, however a SF_6 plasma is not easy to stabilize and Ar can be mixed in to obtain a better result. In Fig. 11 we can see that we obtained a current voltage curve which is typical for an ion-ion plasma. An ion-ion plasma

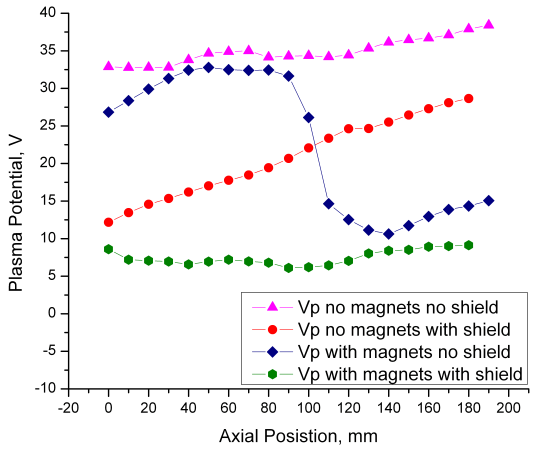

Figure 8. Measurements of the plasma potential with a floating emissive probe along the axis of the discharge tube where 0 mm is the exit of the tube and 100 mm the center of the magnetic field.

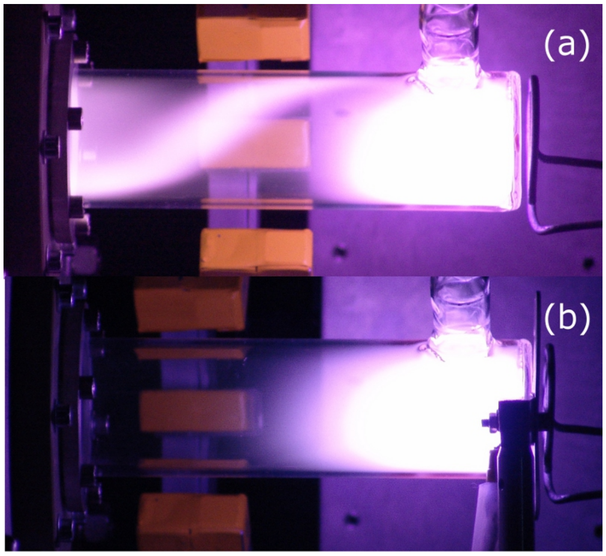

Figure 9. Pictures of the RF plasma discharge with 20 sccm argon, 300 W input power, at a background pressure of around 10^{-3} mbar and 500 G magnetic field (a)without and (b)with a Faraday shield.

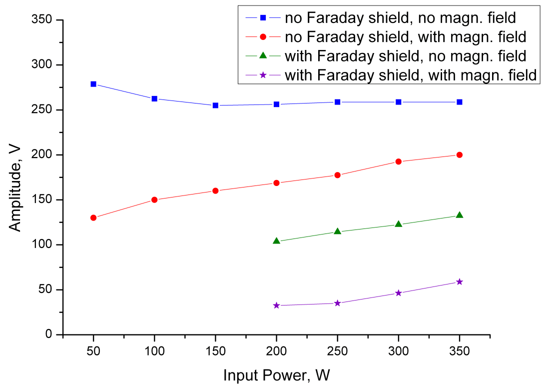

Figure 10. Measurement of the RF fluctuations in the plasma, 4 cm downstream of the magnetic barrier, with and without a magnetic field (around 500 G at the center on the axis) and the Faraday shield over the input power.

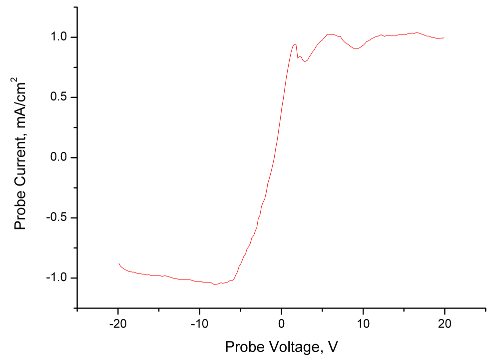

Figure 11. Measurement of an ion-ion plasma in a SF_6/Ar mixture (10 sccm SF_6/20 sccm Ar) with a compensated Langmuir probe at 5x10^{-3} mbar and an input power of 350 W.

curve is ideally symmetrical to the zero point and saturates quickly.

IV. Conclusion

Experiments hint that this strip originates most likely from an E×B drift. The E-field seems to originate out of a capacitive coupling from the antenna to the plasma. This is advantageous since the second PEGASES prototype operates at a lower frequency and uses a ferrite material to concentrate the energy deposit into the plasma. This also means that it operates almost purely inductively and shows no signs of this phenomena even without a Faraday shield. However due to constraints in the equipment and the general layout of the PEGASES prototype switching to the the prototype was not an option and it was necessary to avoid the creation of the strip in the simple discharge tube to conduct our experiments.

A Faraday shield placed between the antenna and the discharge tube prevents the formation of the strip. This shield prevents the formation of an electrostatic field between the antenna and the discharge tube and therefor a capacitive coupling. In the inductive coupled plasma the electrostatic field is not strong enough to form a strip.

We have then measured an ion-ion plasma in our discharge tube with a SF_6/Ar mixture. We can see that the ion-ion plasma density is still very low and needs improvement. With our current setup we can now further investigate the influence of the different parameters, such as gas mixture, gas density, input power, magnetic field strength and magnetic field shape. These experiments can lead to a better ionization efficiency and therefore drastically improve the overall efficiency of the PEGASES thruster.

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