Ion acceleration through a magnetic barrier
Toward an optimized double-stage Hall thruster concept

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Abstract: The idea behind the concept of double-stage Hall thrusters (DSHT) is to decouple ionization and ion acceleration by adding a plasma source, upstream of the magnetic barrier that can be operated independently from the dc applied voltage of the acceleration stage. Although this concept is very appealing and should allow wider regimes of operations, the numerous attempts at designing double-stage Hall thrusters have met with limited success. In this paper, we present a review of the main DSHT designs described in the literature. We discuss the relevance of the DSHT concept, and, on the basis of simple physics arguments and simulations, we propose a new design, called ID-HALL (patent pending), where the ionization stage is an inductively coupled plasma source whose coil is located inside the inner cylinder of the thruster.

I.Introduction

IN a Hall thruster the plasma is formed in a channel between two concentric ceramic cylinders[1, 2]. Xeon is injected from the anode side at one end of the channel and is ionized by electrons emitted from an external hot cathode and accelerated by a dc voltage between cathode and anode. Ions generated in the channel are accelerated through the exhaust plane by this potential drop. A radial magnetic field in the exhaust region forms a barrier to electron transport and lowers the axial electron conductivity, leading to an increase of the axial electric field in that region. The electrons emitted by the external cathode are accelerated by this electric field and ionize the gas injected from the anode. The ions, practically insensitive to the magnetic field are extracted and accelerated out of the channel by this electric field.

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The residence time of the electrons in the plasma is considerably increased by the radial magnetic field, allowing efficient ionization at low gas pressure. The combination of the radial magnetic field and the axial electric field in the exhaust region leads to a large azimuthal electron current, the Hall current. Electrons are trapped by the magnetic field and only collisions (including electron-wall collisions) or turbulence can lead to electron transport across the magnetic field barrier.

In a single stage Hall thruster, the same electric field is responsible for ion extraction and acceleration as well as for ionization (electrons entering the channel from the cathode side gain energy from this field and ionize the flow of neutral atoms emitted on the anode side). This implies that specific impulse (i.e. ion velocity) and thrust are not independent. One can therefore imagine another design of Hall thruster where ionization is not (or not only) performed by electrons incoming from the external cathode and accelerated by the axial electric field, but by a separate plasma source placed upstream of the magnetic barrier and acceleration region. The power deposited in this plasma source could be adjusted separately from the applied voltage between cathode and anode. This configuration is called a double-stage Hall thruster (DSHT) since ionization and acceleration are performed in two different stages. In an *ideal* DSHT, ionization would be completely controlled by adjusting the mass flow rate and power deposition in the first stage (ionization stage), while acceleration would be controlled by the voltage applied across the magnetic barrier. However, electrons entering the channel from the cathode side are still needed to neutralize the extracted ion beam in the magnetic barrier. These electrons also "see" the large electric field and potential drop in the magnetic barrier and can be accelerated at high energy and contribute to ionization. This shows that perfect uncoupling between ionization and acceleration is actually not possible. To minimize the role of these electrons in ionization and to limit the total power they absorb, the magnetic field must be adjusted in such a way that the current of electrons entering the channel is kept as low as possible. This is not a simple task since electron transport through the magnetic barrier in Hall thrusters is not well understood. Note that in a single stage thruster operating efficiently, the cathode must be able to provide the electron current necessary to ionize all the flow of neutral atoms injected at the anode. Double-stage operation of a Hall thruster is therefore especially relevant when the applied acceleration voltage is low and not sufficient to provide ionization of the injected gas flow. This is the case for operations at low specific impulse and large mass flow rate or large thrust. Double-stage operation would also be justified when using a gas with mass smaller than that of xenon (eg argon) because, for the same specific impulse, the applied accelerating voltage would have to be significantly lower and possibly insufficient to insure significant ionization in the channel.

Whether or not the *ideal* way of operation of a DSHT, where all the ionization is controlled in the first stage, can be achieved or can lead to good performance is one of the questions that must be addressed in designing DSHTs. Another important question is how to optimize the extraction through the magnetic barrier of all the ions generated in the first stage. The extraction area can be small with respect to the total area of the first stage so that it is essential to efficiently limit the wall losses in the ionization chamber, eg by using magnetic cusps. It is also intuitive that ionization in the first stage should be such that the maximum plasma density be as close as possible to the magnetic barrier so that a maximum of positive ions can be efficiently extracted.

A number of DSHT designs have been proposed and tested along the years. The performance of these thrusters have however not really reached expectations and they were not shown to operate as the "*ideal* DSHT" described above. In many designs, the DSHT was simply built by connecting a given plasma source to a standard single stage Hall thruster.

In this paper, we describe a selection of previous DSHT designs (section II), discuss the requirements for an efficient DSHT concept (section III), and propose a new design (section IV) based on these requirements, and called ID-HALL (**I**nductively coupled **D**ouble-stage **HALL** thruster). Preliminary characterization of the ionization stage is presented.

II.Previous DSHT designs

The brief review below of different types of double-stage Hall thrusters shows that in most cases the performance of these DSHT have not met the expectations and that the relevance of the very concept of DSHT has yet to be demonstrated.

We can distinguish DSHT designs where the ionization stage is in a separate plasma chamber from designs where the ionization stage is in the thruster channel but with separate control of ionization. Examples of these two types of design are described in the two sub-sections below.

A. Ionization stage in a separate chamber

Various plasma sources have been considered for the ionization stage: energetic electrons from a hot cathode in a multicusp chamber (Fig. 1) or a more complex magnetic configuration (Galathea design, Fig. 2), ECR (Electron

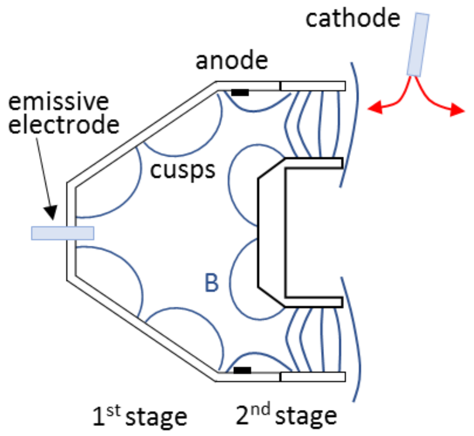

Figure 1: DSHT with an electron bombardment cusped ionization stage (similar to the NASA-173GT developed by Peterson[3]).

Cyclotron Resonance, Fig. 3), and helicon sources (Fig. 4). We briefly discuss below the properties of these DSHT designs.

Figure 1 shows a DSHT where the ionization stage is a multicusp electron bombardment plasma source (a similar design, the NASA 173-GT, has been studied by Peterson[3]). The cusped ionization stage with electron bombardment (electrons of a few tens of eV emitted by an emissive cathode in the first stage) of Fig. 1 is very similar to an electron bombardment gridded ion source[1] where the extracting grids are replaced by a magnetic barrier.

The experimental results on the NASA-173GT reported in the PhD thesis of PY Peterson[3] were disappointing since operations in a single or double-stage mode did not appear to be very different. One could expect that the relative contributions to the overall ionization of the electron source inside the chamber or of electrons coming from the external cathode would be affected by the mass flow rate, applied voltage, or injected electron currents, leading to different properties of the thruster in the double and single stage modes. There was however no clear conclusion in Ref. [3] on the different physics involved in the single stage and double-stage modes or on the advantage of operating in a double-stage mode.

A very interesting concept of DSHT is the SPT-MAG of Morozov and Bugrova[4, 5], based on a semi-galathea magnetic field design (the galathea concept is an efficient magnetic confinement configuration proposed by Morozov[6] in the 1990's). Figure 2 displays the SPT-MAG DSHT design and illustrates the magnetic electron confinement and electrostatic ion confinement obtained in this configuration.

A voltage drop (a few tens of volts) is applied between an intermediate cathode placed in the first stage at the entrance of the channel, and the anode around the myxina and on the chamber wall. The intermediate cathode is emissive and plays the role of an anode for the acceleration stage and the role of a cathode for the ionization stage. Electrons are trapped around the magnetic field lines (see some electron trajectories in Fig. 2a). Because the magnetic field lines are quasi-equipotential while the electron conductivity perpendicular to the magnetic field is low, the applied voltage in the source is distributed between the separatrix line (see Fig. 2) at a potential close to that of the intermediate anode, and the anode. This leads to the formation of a potential well that traps the ions electrostatically and guides them to the channel entrance (see typical ion trajectories on Fig. 2b).

The voltage drop in the potential well also provides energy to the electrons in their cross-field motion from the separatrix line to the anode, leading to ionization and plasma generation in the source. The electron and ion trajectories on Fig. 2 are deduced from a hybrid simulation[7, 8, 10]. In this model the description of ion transport is kinetic while the description of electron is fluid. Ionization is however deduced from a Monte Carlo simulation of electrons transport.

Experimental results on the SPT-MAG[11] showed that this DSHT could operate in two modes: high thrust (eg 190 mN at 300 V and 9 mg/s xenon mas flow rate) or high specific impulse (eg 3650 s at 900 V and 3 mg/s xenon mass flow rate).

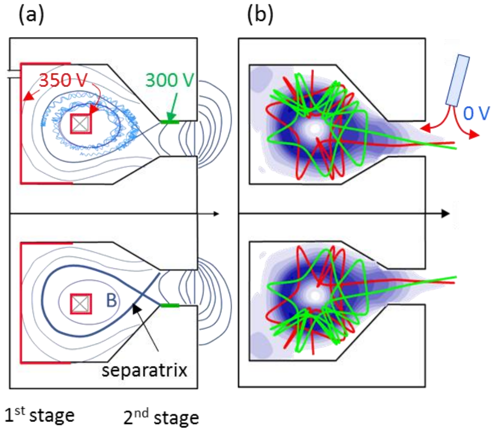

Figure 2: SPT-MAG double-stage thruster using the Galathea concept of Morozov et al. [7-9]. Typical electron, (a), and ion, (b) trajectories from simulations[8, 9] are displayed. The grey levels in Fig. 3b correspond to calculated equipotential contours.

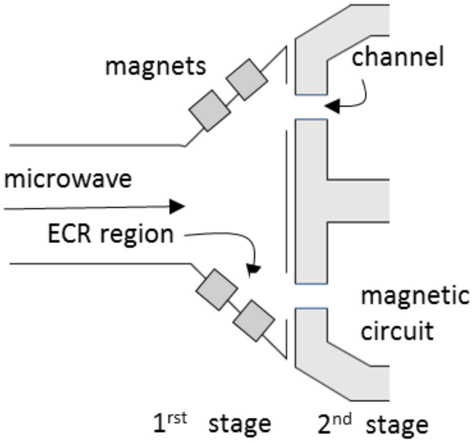

Figure 3: DSHT with an Electron Cyclotron Resonance (ECR) ionization stage[12]

Although this is an interesting result, it is not clear whether this thruster really operated as a DSHT, i.e. if the plasma in the chamber was generated by electrons heated by the applied electric field in the ionization stage or by energetic electrons coming from the external cathode (which corresponds to single stage operation). This is related to another important question, not discussed in the experimental papers, i.e. the role of the intermediate electrode (the cathode of the ionization chamber). The simulations[9] clearly show that this electrode must be emissive to create the potential well in the ionization chamber (otherwise the potential drop takes place in the sheath of the intermediate electrode). Without electron emission and potential well, the first stage does not operate as a separate source of ionization and ionization in the chamber, if present, is only due to electrons coming from the external cathode. In most of the experiments reported in the literature, the intermediate electrode was not emissive and we can conclude that the thruster was not operating in a double-stage mode in these experiments.

The question of ion extraction from the ionization stage in a similar DSHT similar to that of Figure 2 is discussed in an interesting experimental and numerical work by Daren Yu et al.[14, 15].

In the double-stage Hall thruster[12] of Fig. 3 the plasma of the ionization stage is sustained by a microwave field in the conditions of Electron Cyclotron Resonance (ECR). The microwave field is injected axially from the back of the ionization stage and the resonance region is circular, between two ring magnets located a few cm behind the entrance of the Hall acceleration channel. For the microwave field frequency of 4.25 GHz used in these experiments, the resonance magnetic field B_R, defined by $\Omega_{ce,R} = \omega$ ($\Omega_{ce,R} = eB_R/m$ is the electron cyclotron angular frequency and ω the wave angular frequency) is 150 mT which is much larger than that used in the magnetic barrier of a typical Hall thruster, on the order of 15 mT. Due to the large resonance magnetic field and to the proximity between the resonance region and the acceleration region it was difficult to avoid a strong magnetic interaction between the two regions, which was detrimental to a correct operating of the magnetic barrier.

Another important problem mentioned by the authors[12] is that in this ECR DSHT configuration the microwave propagation is cut-off at the critical density defined by $\omega_{pe} = \omega$ (ω_{pe} is the electron plasma angular frequency) which corresponds to $2.2\times10^{11}\ \text{cm}^{-3}$ for a frequency of 4.25 GHz. Optimal values of the maximum plasma density[2] in Hall thrusters are on the order or larger than $10^{12}\ \text{cm}^{-3}$. It seems that the ECR DSHT concept was not further explored due to the limitations discussed above.

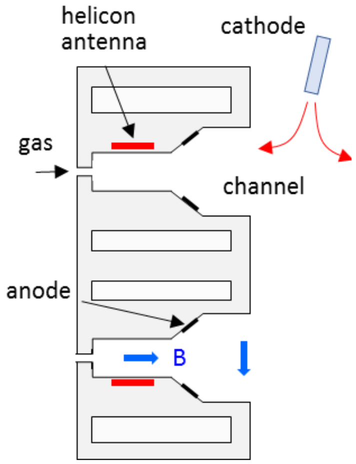

Figure 5: DSHT with an helicon ionization stage in a design similar to that of Martinez et al.[13]

The plasma density in helicon sources can reach very high values, on the order or higher than 10^{13} cm^{-3} so it is very tempting to use these sources as the ionization stage of a DSHT. The concept of annular helicon, to be used as an ionization stage of a DSHT was studied by Palmer et al.[16]. Attempts at developing helicon DSHTs have been reported in Refs. [[13, 17 18]], with a design schematically represented on Fig. 5. Here again, the results did not show an efficient operation in a DSHT regime. For example, in most results of Ref. [[18]], the increase of the measured thrust with helicon power was very small, typically less than a 10 mN per kW of the helicon source, for a DSHT operating with a thrust around 200 mN with the helicon source turned OFF. An important issue in the helicon DSHT design is the question of the connection between the axial magnetic field of the helicon and the radial magnetic field of the acceleration stage. No details on the magnetic field configuration were given in the references above. On the other hand Harada et al.[19] demonstrated "electrostatic acceleration from a helicon plasma using a cusped magnetic field", with an interesting design that could be called "helicon double-stage cusped-field thruster" or "helicon double-stage cylindrical Hall thruster". They were able to extract ions from the helicon plasma under conditions where the cathode-anode voltage was not sufficient to sustain the plasma (proving that the thruster was really operating in a double-stage mode). The performances of this thruster were however not measured.

A. Ionization stage in the channel

We show here two examples of DHST with the ionization stage inside the channel.

In the DSHT of Fig. 6 a microwave field is injected in a cylindrical cavity-resonator behind the channel. The 5.8 GHz microwave field enters the channel through a quartz window and propagates into the acceleration channel. The length of the cylindrical cavity-resonator can be optimized with a plunger. According to the authors of Ref. [[20]], the microwave propagates along the dielectric-plasma interfaces, i.e. the plasma is excited in a surface-wave mode, allowing plasma densities above the critical density.

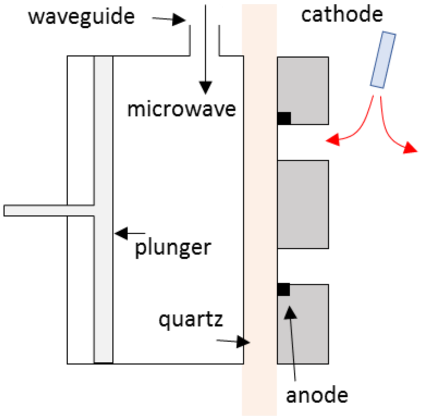

Figure 6: DSHT with a microwave ionization stage[20]

Measurements on this surface-wave double-stage Hall thruster (SW DSHT) showed that this thruster could operate in a double-stage regime. For example it was possible to extract ions through the magnetic barrier even for very low voltage between cathode and anode, i.e. without significant ionization due to electrons emitted by the external cathode and entering the channel. The ion current at these low voltages was however small, about ten times lower than the current corresponding to full ionization of the injected gas flow. An interesting feature of this SW DSHT is that ionization due to the surface wave electron heating takes place very close to the magnetic field barrier. Ions generated in this region can therefore be efficiently extracted and accelerated by the axial electric field before they are lost to a wall.

Another example of DSHT with ionization stage inside the channel is the double peaked magnetic field design of Fig. 7[14, 15]. In this concept the ionization stage consists of another magnetic barrier placed between an intermediate electrode and the anode, upstream of the magnetic barrier of the acceleration stage. A voltage is applied between the intermediate electrode and the anode and this voltage can be controlled independently from the accelerating voltage. This concept implies a relatively long channel (5 cm). Simulations[15] showed that the electron-ion recombination at the channel walls is enhanced and that a non-negligible part of the total ionization was actually taking place in the acceleration stage.

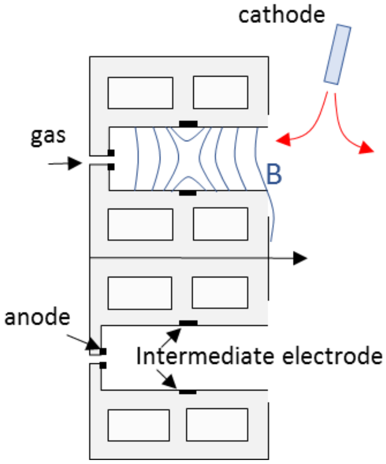

Figure 7: DSHT with a double peaked magnetic field in the channel[21, 22]

III. Issues in the DSHT concept - Toward an optimized design

As said above, the different attempts at designing double-stage Hall thrusters were not really successful and we try, in this section, to analyze the reasons for this limited success.

A first issue is that ionization by the electrons emitted by the external cathode and which gain energy in the accelerating region are still present in a DSHT and are able to ionize the neutral flow as in a single stage Hall thruster. Operation in a double-stage mode at high voltage is therefore not really useful since most of the ionization can be performed by these electrons unless there is a way to limit or control the current of electrons entering the channel from the cathode side. This would need a complete reconsideration of the magnetic field design in the acceleration stage. If the magnetic field in the acceleration stage is kept the same as in a single stage thruster, operation in a double-stage mode would be more useful at low voltages, i.e. under conditions where ionization provided by the electrons emitted by the external cathode would not be sufficient to maintain the plasma. In that case the ionization stage would fully play its role and the thrust of the DSHT could be adjusted by changing the power deposited in the ionization stage and the mass flow rate of the injected gas, independently of the accelerating voltage. This type of operation is well-suited to the use of lighter gases such as argon where the same ion velocity or specific impulse as in xenon can be achieved at lower voltages.

Efficient operation of a DSHT is possible only if most of the ions generated in the ionization stage can be extracted through the magnetic barrier. This is another important issue in the design of DSHTs. In a gridded ion thruster, a large part of the ions generated in the plasma source can be efficiently extracted and accelerated through the grids. The physics of ion extraction through a magnetic barrier is much more complicated since extraction is possible only if electrons from the external cathode can themselves cross the magnetic barrier to neutralize the ion beam. There is no theory on ion extraction across a magnetic barrier and there has been no systematic experimental or numerical study of this concept. The different attempts at designing DSHTs have been very empirical and consisted in connecting a plasma source to the channel of a single stage Hall thruster.

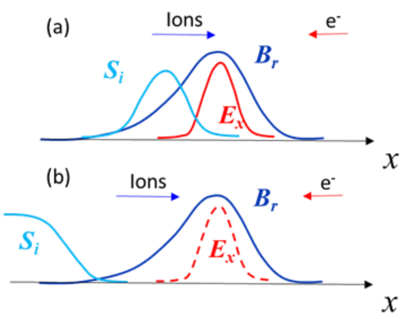

Figure 8: Relative positions of the radial magnetic field, axial electric field, and ionization rate in the acceleration region of (a), a single stage HT, (b), a DSHT

At this stage, it is useful to reconsider the physics of a single stage Hall thruster and the reasons for its remarkable efficiency. An important aspect of ion extraction in a Hall thruster is that the ionization and acceleration regions overlap (Figure 8a). If ions are generated upstream, far from the acceleration region (Figure 8b), 1) they can reach the channel walls and be lost before being extracted, 2) the conditions for optimized electron transport (instabilities ?, electron-wall interaction ?) across the magnetic barrier may not be met. The magnetic barrier of a Hall thruster has been optimized for single stage operation where the ionization and acceleration regions overlap and it seems (and Particle-In-Cell simulations – to be published – confirm) that ion extraction with the same magnetic field profile and non-overlapping ionization and acceleration regions (Fig. 8b), as in most previously developed DSHTs, would be very difficult. Looking at Figure 8b, it is difficult to imagine what could be the axial electric field profile in the DSHT case that could at the same time extract the ions from the plasma generated far away from the magnetic barrier, and ensure electron transport across the magnetic barrier (for whatever cross-field transport mechanism).

We conclude that one solution that could significantly improve the efficiency of DSHTs would be to design the ionization stage so that the ionization region is as close as possible, and if possible inside the magnetic barrier in the region upstream of the maximum B field) of the acceleration stage, as in Fig. 8a.

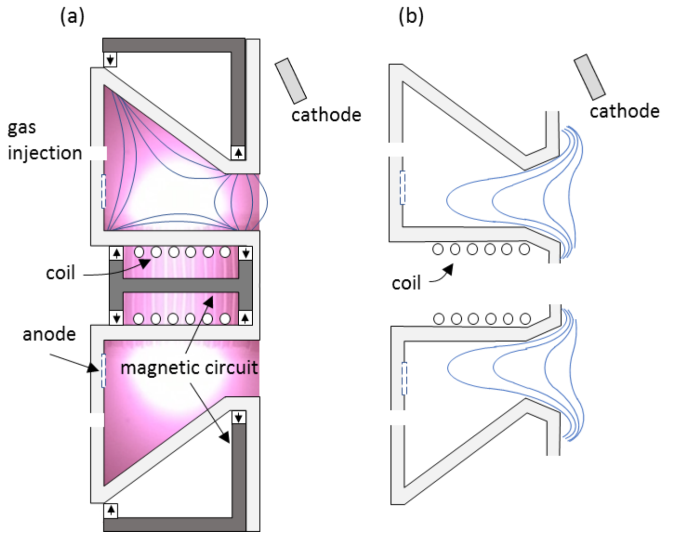

Figure 9: The ID-Hall Double-Stage Hall Truster. (a) version with internal cusps; (b), version with magnetic shielding. An image of the light emitted by the plasma (in argon) is superimposed to the diagram of the DSHT in (a).

IV. A new DSHT concept: ID-HALL – Principles and characterization of the ionization stage

A.The ID-HALL concept

The **ID-HALL** DSHT (patent pending) is an **I**nductively coupled **D**ouble-Stage **HALL** Thruster schematically represented in Fig. 9. The ionization stage is an RF inductively coupled plasma with a coil placed inside the inner cylinder of a Hall thruster. This preliminary design operates at low power with a magnetic field configuration generated by magnets, and is aimed at studying the basic physics of the thruster. Two designs are shown in Fig. 9: one with internal cusps, and the other with magnetic shielding.

It has been shown[23, 24] that a plasma generated by an internal coil with a central cylindrical magnet can reach high densities and is very well localized in the form of a torus around the cylindrical coil. This is because electrons are moving back and forth along the axial magnetic field, while being heated by the azimuthal electric field induced by the inductive coil. Figure 9 shows a picture of the light emitted by the plasma, superimposed to a diagram of the thruster (the picture has been taken in argon with the ionization stage operation only, and without the magnetic field of the magnetic barrier). Therefore, this configuration of inductively coupled magnetized plasma seems well adapted to a geometry of a Hall thruster. The position of the coil can be adjusted to move the ionization region as close as possible to the magnetic barrier.

The axial component of the magnetic field around the inner cylinder plays an important role in trapping the electrons in the region where they can be heated by the azimuthal RF field induced by the coil. This axial component must be coupled to the radial magnetic field of the magnetic barrier in the acceleration channel. In order to confine the plasma as much as possible and to limit the charged particle losses to the walls, the magnetic circuit is designed so that the magnetic field has components parallel to the walls. This implies the presence of magnetic cusps, which can be seen on Fig. 9a. A magnetic configuration similar to that of a magnetically shielded thruster[25, 26], without the two cusps in the back of the thruster is also possible, as indicated in Fig. 9b.

B. Preliminary characterization of the ionization stage

In this section we report measurements of the plasma characteristics of the ionization stage only, without the accelerating channel and magnetic barrier. Figure 10a shows the experimental set-up. The antenna is inserted in a dielectric tube and is driven at 13.56 MHz by a RF power supply (a lower frequency in the MHz range will be used in the final prototype). A magnetic circuit is inserted inside the coil to confine the plasma as shown in Figure 10b.

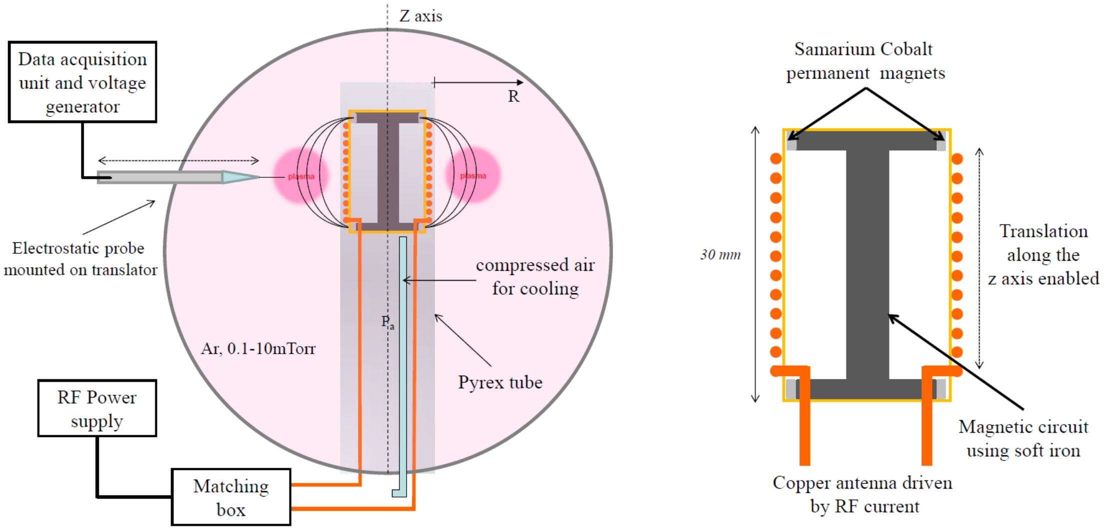

Figure 10: (a) Experimental set-up; (b) view of the RF coil and magnetic circuit

A homemade 50 µm radius tungsten wire Langmuir probe (passive RF compensation) and associated data acquisition system have been used to measure the EEPF (Electron Energy Probability Function), electron density and effective electron temperature.

The plasma is very dense and has a toroidal shape around the dielectric tube as shown in Figs 9 and 10a. Figure 11a shows the measured electron density and electron temperature at 3 mTorr, 125 W (magnetic field 140 G on the dielectric surface), as a function of distance from the dielectric surface, along a line going through the middle of the plasma in the axial direction. The plasma density is higher than $3\text{x}10^{11}$ cm^{-3} at a radial position 1 cm away from the dielectric surface and decreases by more than a factor of 2 over 1 cm in the radial direction. No reliable data were obtained closer to the dielectric surface as the strong RF power disturbs the measurements. Judging from the large density gradient at 1 cm from the surface, it seems that the plasma density closer to the dielectric surface probably reaches values as high as $5\text{x}10^{11}$ cm^{-3}. The electron temperature is about 7 eV close to the dielectric surface and decreases to 3 eV a few cm away from the surface.

As expected, the plasma density (Figure 11b) varies linearly with the absorbed power (the experiments are performed under constant gas pressure and quasi-constant neutral density, i.e. no strong neutral depletion).

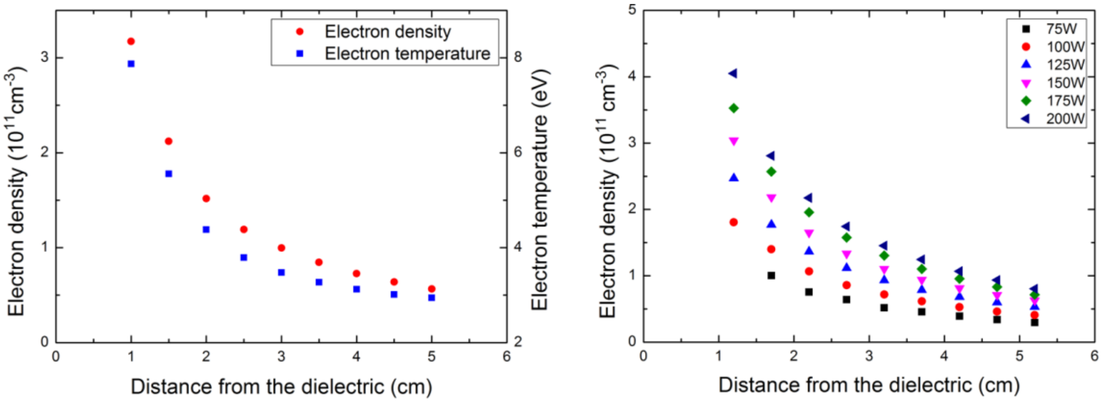

Figure 11: (a) Plasma density and electron temperature as a function of radial distance from the dielectric surface in argon, 3 mTorr, 125W absorbed power; (b) Plasma density profiles in the same conditions for different values of the absorbed power. The magnetic field on the dielectric surface is 140 G.

Measurements of the plasma density as a function of pressure at 125 W (Fig. 12a) show that the plasma can be sustained at low pressure, 0.5 mTorr or below (down to 0.1 mTorr in these conditions), with densities still in the 10^{11} cm^{-3} range. The effect of the magnetic field can be clearly seen on Figure 12b where the density profile is shown as a function of the magnetic field intensity (the magnetic field can be varied by changing the intensity of Samarium Cobalt magnets represented in Figure 10b). Without magnetic field (pink triangles on Fig. 12b) the plasma density next to the dielectric cylinder remains below 10^{11} cm^{-3} and the plasma spatial profile stays flat, with a maximum at 3.2 cm from the dielectric surface. In that case the plasma diffuses in the whole volume of the vacuum chamber. With magnetic fields between 100 and 200 G on the dielectric surface, the plasma density is larger than 2x10^{11} cm^{-3} 1 cm away from the dielectric surface and decreases sharply from this point: the spatial extension of the plasma is limited by the magnetic field, and its maximum value is significantly larger.

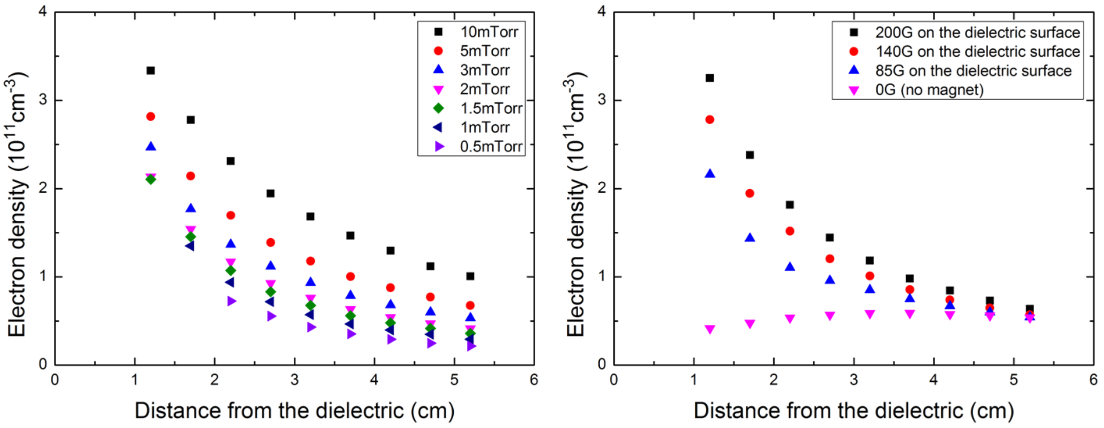

Figure 12: Radial profiles of the measured plasma density, (a) for different pressures (at 125 W, 140 G magnetic field on the dielectric surface), (b) for different magnetic field intensities on the dielectric surface (at 125 W, 3 mTorr)

V.Conclusion

The concept of Double-Stage Hall Thruster consists in extracting ions from a plasma source through a magnetic barrier. Ionization and acceleration cannot be completely independent because electrons entering the channel from the cathode side gain energy from the applied accelerating dc field, but it should be possible to operate efficiently in a double-stage mode at low extracting voltages, i.e. when electrons from the external cathode do not gain enough energy to ionize the injected gas. This type of operation is well suited for gases lighter than xenon, for which the same specific impulse as in xenon is obtained at lower voltages. In these conditions, adjusting the power deposited in the ionization stage and the mass-flow rate would allow to control the thrust while the specific impulse would be independently controlled by the applied dc voltage.

Although the DSHT concept seems very appealing and promising, there has not been any clear proof that ions can be efficiently extracted from a plasma source through a magnetic barrier. This is certainly related to the complex physics of plasma transport through a magnetic barrier. An important aspect of single stage Hall thrusters is that the ionization and acceleration regions are very close together and even overlap[27]. We think that this overlapping between ionization and acceleration regions is a necessary condition for efficient ion extraction through a magnetic barrier in Hall ion sources. Therefore a Double-Stage Hall Thruster should be designed in such a way that the plasma generation in the ionization stage be as close as possible to the magnetic barrier where the acceleration region is located.

We propose a new concept, called **ID-HALL** (for **I**nductively Coupled **D**ouble-stage **HALL** Thruster) where the ionization stage consists of a radiofrequency inductively coupled plasma with a coil inside the central cylinder of the Hall thruster channel. This design is particularly well adapted to the concentric cylinder geometry of a Hall thruster, and allows, when a suitable magnetic field configuration is used, to generate a high-density plasma that is confined in a region whose position with respect to the acceleration region can be easily adjusted.

The ionization stage has been tested and measurements show that a donut-shaped, high density plasma (more than $2\text{x}10^{11}$ cm^{-3} for a moderate power of 125 W at pressure on the order of 1 mTorr) forms around the central cylinder. The shape and location of this plasma are particularly well-suited for ion extraction through a Hall magnetic barrier. Ion extraction measurements will be performed in the next few months.

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