NON CONVENTIONAL PROPELLANTS FOR ELECTRIC PROPULSION APPLICATIONS

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ABSTRACT

Xenon production is a highly expensive process that involves many stages of air refrigeration and expansion. Xenon cost depends also from the increasing worldwide demand of this gas due to its application in automotive industry, medicine and space propulsion, but in a view of ecological sustainability of the production processes and greenhouse gases reduction this would go in an opposite direction. In fact even if Xenon is a sort of waste of Argon production, its very low percentage in air composition (0.000009% compared to 0.917% of Argon) makes the separation of the same amount of gas extremely expensive. But while the production efficiency is not easy to increase it is still possible to reduce the Xenon demand. The objective of this paper is to assess the possibility to substitute Xenon used for space application with a more ecologically sustainable gases and evaluate the benefits of this choice. The assessing has been made evaluating different EP technologies respect to their usage with Argon and Krypton, and comparing their performances with the original ones obtained using Xenon.

I. INTRODUCTION

Xenon and other noble gases are widely used in industry thanks to their ability to ionize at relatively low voltages. In particular Xenon's first ionization energy is approximately 12.1 eV [1], lower than the other perfect gases except from Radon, that due to its intrinsic radioactivity is not widely used. Ionized Xenon is used in a wide range of application such as fluorescent lightning, plasma displays, flash lamps. Excited xenon is used in excimer lasers for eye surgery and semiconductor lithography. In atomic industry Xenon and other perfect gases are used for ionization chambers for measuring radiations. In medical applications Xenon is almost an ideal anesthetic with minimal side effects, and ^{133}Xe is used as radioisotope. Liquid Xenon is also extensively used in bubble chambers.

Xenon and other rare gases are produced almost exclusively as a byproduct of the separation of Nitrogen and Oxygen from air for industrial uses. Only the larger plants can implement dedicated structures to perform this additional process, meaning that Xenon is produced in small quantities and not everywhere. The main reason is that the percentage of Xenon in the atmosphere is extremely low, making economically sustainable the production of such rare gas only in plants capable of processing at least on the order of thousand tons of air per day. The average air composition is the following:

Nitrogen	78.08400 %
Oxygen	20.94800 %
Argon	0.934000 %
Carbon dioxide	0.037000 %
Neon	0.001818 %
Helium	0.000524 %
Krypton	0.000114 %
Hydrogen	0.000050 %
Xenon	0.000009 %

Table 1 Atmosphere composition by volume [2]

From Table 1it can be seen the extremely low concentration of Xenon in the atmosphere. To give an order of magnitude a plant capable of processing 1000 tons/day day of air (290 million of m^3/yr) will be able to produce only 1.2 kg/day of Xenon, at typical 70% production efficiency. Krypton abundance, and so extraction, is ten time higher, making its final price almost ten times lower than Xenon. In fact the latter prices are presently ranging around 12 Euros per liter, while Krypton costs around 1 Euro per liter. It is not economically convenient to install a plant capable of producing only rare gases, even if theoretically such process exists. As a consequence of this situation the production of Xenon and Krypton is totally related to the production of Oxygen. If one consider the latter somehow fixed, it is possible to say that Xenon price is currently driven almost entirely by the demand. In addition the variation in the price of Xenon is independent of the Krypton price and vice versa because even if many applications are common, some are specific to one or to the other [3].

From the environmental point of view the production of 1 m^3 of Xenon has an enormous cost, because processing 1 m^3 of air requires 1 kWh of electric power on average. At the same time this cost is not avoidable for the before mentioned reasons: even if the demand of Xenon and Krypton drops to zero the same amount of energy will be used to produce Oxygen, because the energy costs of collecting and refining the gases is negligible respect to the overall energy cost. For this reason even if it is not possible to reduce the global production of greenhouse gases caused by Oxygen/Xenon production it is still possible to avoid increasing the demand in order not to justify the building of new partially or completely dedicated plants. This is even more important considering that the demand of Xenon for space propulsion application is foreseen to substantially increase in the next future. Hence finding a valid alternative is mandatory if the goal is to keep the European space sector away from the high costs and the high fluctuations of Xenon price for propulsive applications.

For this reason an assessment on the possibility to use conventional EP thrusters with other noble gases than Xenon is performed. The analyzed classes of EP thruster technology are Grid Ion Thrusters GITs, Hall Effect Thrusters HETs High Efficiency Multistage Plasma Thrusters HEMPTs, and Helicon Plasma Thruster. Most of these thrusters produce thrust by expelling an energetic ion beam, the ions of which are generated in a plasma discharge. Helicon Plasma Thruster expels a plasma beam with no need for neutralization.

This article is organized in 8 sections. Section 2 reviews general considerations on thruster operation with different noble gases. Section 3 and 4 show examples of GIT and HET operation on various noble gases collected from published literature. In section 5 a comparison of experimental results obtained from HEMPT thruster operation on Xenon and Krypton are reviewed. In section 6 helicon thruster technology is presented and discussed. Another important point to be taken into account concerns testing issues. In fact, the test facilities presently engaged in EP testing have high vacuum pumping systems (typically based on cryogenic pumping) designed to pump Xenon. While the change from Xenon to Krypton or Argon as propellant does not impose major problems onto the existing pumping systems, the dynamic pumping of Nitrogen, Oxygen or Hydrogen components at high vacuum levels is a major problem. These issues are discussed in the section 7. Finally, the consequences operating with propellants different to Xenon are concluded in section 8.

II. General Considerations

Argon, Krypton and Xenon are traditionally used in electric propulsion because of their chemical inertness, even only the last one has been extensively used in the actual space environment. The motivation is mainly based on the lower Xenon ionization energy (see Figure 1) and the higher mass respect to the other gases. Lower ionization energy means that less power is consumed for the process of propellant ionization, which represents pure loss mechanism for the thrusters under consideration. This power loss often is referred to as ionization costs. Obviously, the higher the ionization costs, the lower is the available power for thrust generation. In addition Xenon has a higher ionization rate already at lower electron energies. As a result, at a given electron temperature in the discharge plasma, a higher neutral flow will be ionized per time unit which increases the mass utilization efficiency and thus the specific impulse.

Regarding system level aspects, Xenon exhibits the highest boiling point and the highest density in either the liquid or gas phase [3]. This maximizes its storability and reduces the costs of the propellant storage system on the satellite.

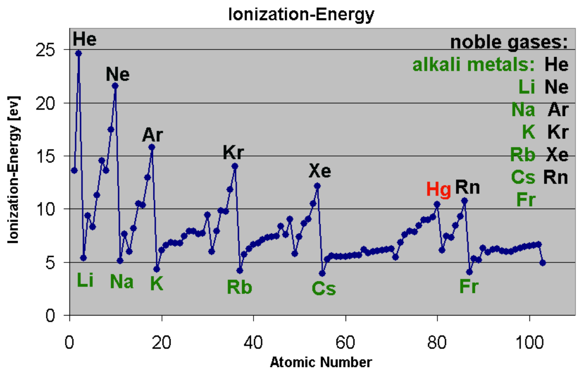

Figure 1 First ionization energy of various elements

Due to the well known Xenon economical and procurement problems exposed above some authors had focused their attention to investigate the possibility to use other gases for space propulsion application. The assessments often concern the comparison between Xenon and Krypton, with the last one seen as the most promising low cost propellant for future missions. It should be finally highlighted that collisional radioactive model, which are a fundamental tool for spectroscopy and theoretical investigation on different propellants are already available also for Argon and Neon [4,5].

III. Grid Ion Thrusters

Welle [3] performed a theoretical assessment of the performance of an ion engine fed with Xenon, Krypton, and Argon. Conclusions shows that with lighter gases, as expected, ionization cost will go up while utilization efficiencies will go down, but this should be smaller than 10%. This means that for an orbital transfer mission from LEO to GEO (ΔV = 6000 m/s) with Isp = 2000s a Krypton propelled mission will take 16% longer than a Xenon mission, and an Argon propelled mission will require 63% more time. Depending on the mission this could be a drawback or not. For a commercial satellite this delay could result in substantial non-operational losses but at the same time the cheaper propellant cost would provide a not negligible saving. A trade off is obviously required, but from the point of view of scientific mission the low cost and the high specific impulse can really let Krypton Ion Propulsion be an affordable solution for long range missions. NASA interest in this topic has been clear since before 2000, ranging from the interest in developing a high specific impulse (>10000 s) 10-30 kW Krypton Ion Engine in support to the Interstellar Probe project [6] to subsequent studies about electric propulsion concept for space explorations [7]. This last work from Gilland et al. provides an interesting comparison between the efficiencies of a representative ion thruster fed with different propellants. As from Figure 2, plotted from Gilland data, it can be seen that for an application like the previously mentioned interstellar ion engine, for the required specific impulse, the different in efficiency between Xenon and Krypton can be considered negligible.

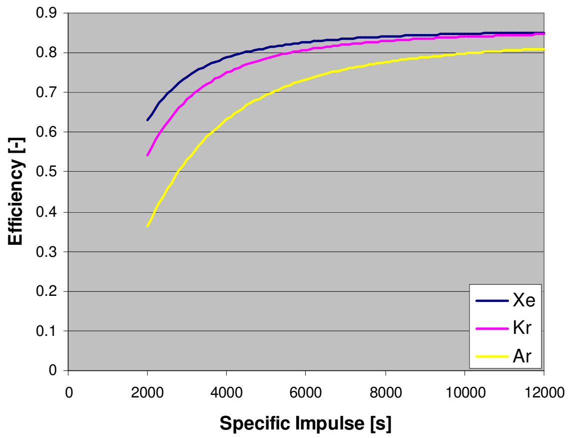

Figure 2 Representative ion thruster efficiency, η, for Xenon (Xe), Krypton (Kr), and Argon (Ar).

IV. HALL EFFECT THRUSTERS

Linnell et al. [8] focused their attention on an Hall thruster following the interest of the electric propulsion community on Krypton relatively large specific impulse as compared to Xenon and its potential to operate with comparable efficiencies.

Linnell work studied and addressed the reasons for the krypton efficiency gap separating the Hall thruster anode efficiency into four separate terms: the charge utilization, the propellant utilization, the current utilization, and the voltage utilization. The latter is a measurement of the effective axially directed ion kinetic energy in electron volts as compared to the thruster discharge voltage. Results show that the propellant utilization and beam divergence appear to be the dominant factors responsible for the efficiency gap: respect to Krypton, Xenon propellant utilization is about 5 to 10% better and beam divergence efficiency (hence voltage utilization) is 8% higher. This lead to a total anode efficiency 5 to 15% higher for Xenon. At the same time Linnell shown that this gap can be reduced: increasing the anode flow rate produce many positive effect, such as the improvement of krypton’s anode efficiency by almost 8%, the increase of the ionization rate and hence of the propellant utilization, the increase in current utilization efficiency and in beam divergence, allowing ions to start accelerating earlier in the acceleration zone, and so reducing the divergence. A successive paper from Linnell et al. [9] demonstrated that krypton acceleration zone is actually longer than the Xenon one.

As a confirmation of these conclusions a previous work of Garrigues et al. [10] shown an analogue 15% difference between experimental efficiency with an SPT-100 thruster fed with Xenon and Krypton and about 10 mN difference in terms of thrust with equal applied voltage. Another important aspect is covered by the work of Kieckhafer et al. [11] demonstrating that erosion rate due to sputtering is lower for Krypton than other propellants at very high energies, other than confirming that it provides the highest Isp for a given acceleration voltage, minimizing the large ionization cost at high exhaust energies.

V. HIGH EFFICIENCY MULTISTAGE PLASMA THRUSTERS

Whilst the concepts for GITs and HETs have been developed in the 1960s, High Efficiency Multistage Plasma Thrusters invented by Thales Electron Devices GmbH TEDG represent a novel thruster concept. It is originally derived from travelling wave electron tubes, and after first concept ideas end of the 1990s followed by a first patent in 1998 [12], HEMPT development has been performed since 2000. Due to the successive progress in development on both component and system level, TEDG has been awarded the HEMPTIS (HEMP Thruster In orbit verification on SmallGEO) project by German Space Agency DLR. In course of this a HEMPT ion propulsion system is currently being developed and qualified and will be flown on ESA’s SmallGEO satellite.

In an earlier stage of development the HEMPT demonstrator model DM8 has been investigated regarding its operational and performance characteristics using Xenon and Krypton propellant. This thruster was optimized for medium to high specific impulse (2500 … 3000 s) operation with Xenon at input power levels up to 2.5kW. The development and test program of HEMPT DM8 was performed in 2005 [13] and 2006 [14] and has been supported by German Space Agency DLR under contract number 50JR0341. Testing infrastructure has been TEDG’s ULAN facility incorporating a 2.4m diameter per 4.5m length vacuum chamber with a cryogenic pumping system. Thruster performance was measured by means of a thrust balance. The data presented below have been measured for a similar propellant mass flow fed to the thruster ($\dot{m}_{Xe} = 1.89 mg/s$ and $\dot{m}_{Kr} = 1.81 mg/s$). The resulting pressure in the vacuum facility with operating thruster was always below $p \le 8 \times 10^{-6} mbar$.

In general with both Xenon and Krypton the thruster has operated completely stable in the entire parameter range.

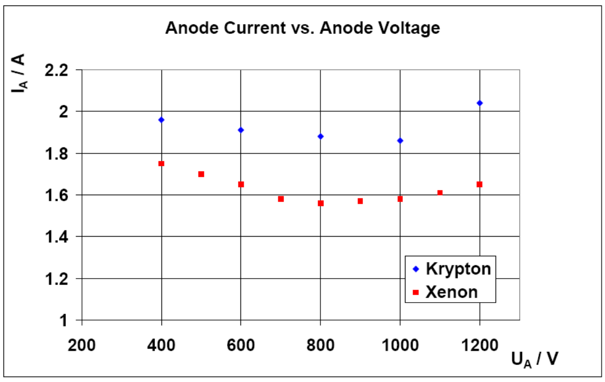

Figure 3 Anode current as a function of anode voltage for Xenon and Krypton operation at a mass flow of 1.89 and 1.81 mg/s, respectively.

shows the current-voltage characteristics. As typical for HEMPTs the anode current stays mainly flat when the voltage is varied. This is observed for both Xenon and Krypton operation.

Although the particle flow is by a factor of 1.49 higher in case of Krypton the emitted ion current - in case of HEMPTs the emitted ion current is practically equal to the anode current – is only about 1.23 times higher. Assuming similar local electron temperatures, this is due to the lower ionization rate which results from the differences in ionization cross section and threshold as indicated in section II. Consequently, the mass utilization efficiency for Krypton operation is about 83% of that of Xenon under the assumption of a similar ionization state distribution.
Assuming similar acceleration efficiency and taking into account the ratios in ion current of a factor of about 1.23 from above, one would expect the thrust ratio to be $\frac{T_{Xe}}{T_{Kr}} \approx \frac{1}{1.23} \cdot \sqrt{\frac{M_{Xe}}{M_{Kr}}} = 1.02$ and for the ratio of the power-to-thrust-ratios $\frac{PTTR_{Xe}}{PTTR_{Kr}} = 0.8$. The actual measured data, given in Figure 4 and typically show $\frac{T_{Xe}}{T_{Kr}} \approx 1$ and $\frac{PTTR_{Xe}}{PTTR_{Kr}} \approx 0.8$. These experimental observations essentially confirm the theoretical considerations.

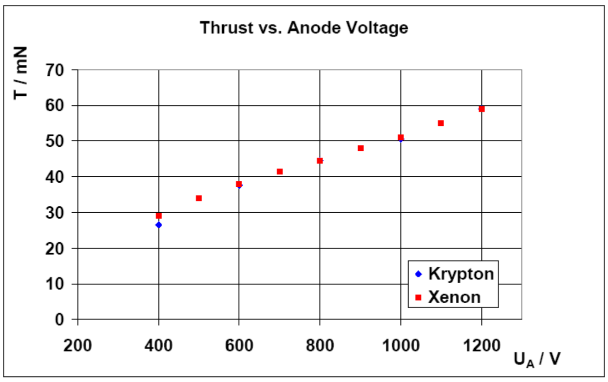

Figure 4 Thrust as a function of anode voltage for Xenon and Krypton operation at a mass flow of 1.89 and 1.81 mg/s, respectively.

Thrust values range from about 30mN at 400V of anode voltage to about 60mN at 1200V, respectively. The observed increase of thrust with anode voltage for both propellants is somewhat higher than the expected square root dependence on the anode voltage and results from the optimization towards higher specific impulses and thus anode voltages. The thrust values obtained with Krypton are slightly lower to equal compared to those with Xenon and thus follow the theoretical considerations from above.

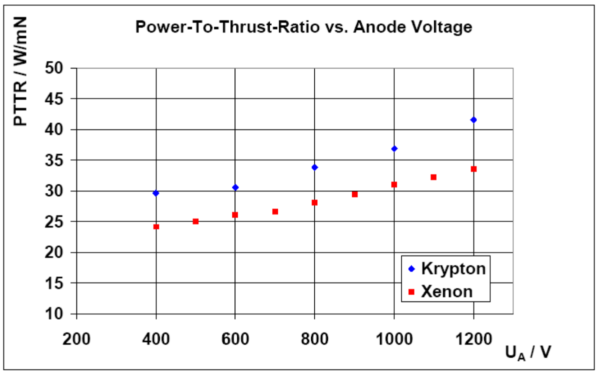

Figure 5 Power-to-thrust-ratio as a function of anode voltage for Xenon and Krypton operation at a mass flow of 1.89 and 1.81 mg/s, respectively.

The PTTR values for Xenon range from 24W/mN at 400V of anode voltage to 34W/mN at 1200V, whilst those for Krypton are 29W/mN at 400V to 42W/mN at 1200V. For both propellants the power-to-thrust-ratio increases less with increasing anode voltage than the expected square root dependence on the anode voltage. As for the thrust, this is firstly due to thruster optimization towards high specific impulses and hence anode voltages. Secondly, this behavior is expected since the relative contribution of the acceleration costs reduces with increasing anode voltage. The relatively higher values obtained for Krypton follow the theoretical considerations from above.

From the considerations and observations made so far and assuming that the propellant mass utilization efficiency scales with the ratio out of ion current to particle flow, the ratio of the specific impulses for Krypton and Xenon at a given anode voltage is expected to be $\frac{ISP_{Kr}}{ISP_{Xe}} \approx \frac{1.23}{1.49} \cdot \sqrt{\frac{M_{Xe}}{M_{Kr}}} \approx 1.03$ The experimentally determined evolution of the specific impulse versus anode voltage is shown in Figure 6.

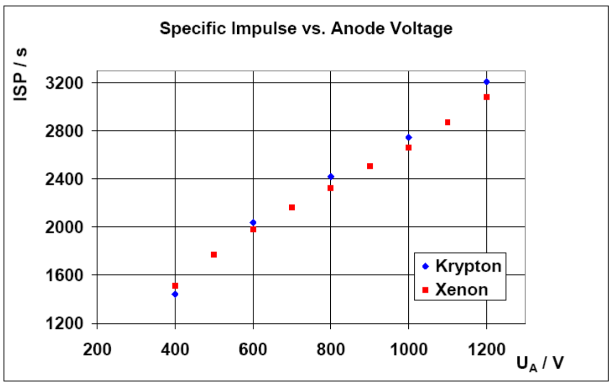

Figure 6 Specific impulse as a function of anode voltage for Xenon and Krypton operation at a mass flow of 1.89 and 1.81 mg/s respectively.

As the thrust, the specific impulse for both propellants increases with anode voltage somewhat more than expected resulting from the optimization towards higher specific impulse values. Comparing the specific impulses, Krypton yields a factor of about 1.03 to 1.04 higher values, which is consistent with the theoretical expectation from above.

In summary the main difference so far is due to the reduced mass utilization efficiency which for Krypton amounts only about 83% of that for Xenon. In addition, one would expect somewhat increased ionization costs due to the ionization potential being about a factor of 1.2 higher. On the other hand the ionization costs for plasma production in case of a HEMPT are only about 10% of the total discharge power. Therefore the ratio of ionization costs entering the anode efficiency represents a small contribution of about 2%. As a result the ratio of anode efficiencies is expected to be about $\frac{\eta_{Xe}}{\eta_{Kr}} \approx \frac{1.02}{0.83} = 1.23$

The experimentally determined anode efficiency, derived from the measured thrust, propellant flow and electrical parameters as $\eta_A = \frac{T^2}{2 \cdot \dot{m} \cdot U_A \cdot I_A}$ as a function of anode voltage is shown in Figure 7 .

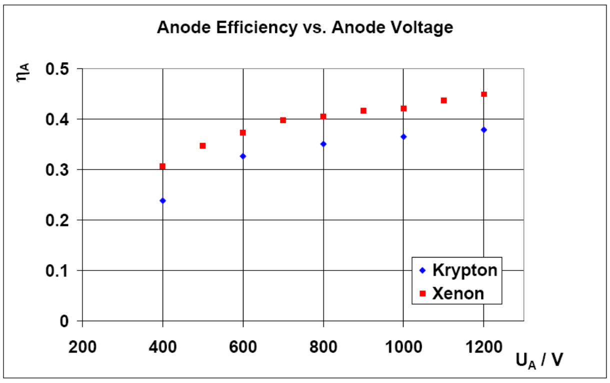

Figure 7 Anode efficiency as a function of anode voltage for Xenon and Krypton operation at a mass flow of 1.89 and 1.81 mg/s, respectively.

Due to thruster optimization towards higher specific impulse levels the anode efficiency rises with anode voltage for both propellants. Highest values are obtained at 1200V and are about 45% for Xenon and 38% for Krypton operation corresponding specific impulse values of about 3100s to 3200s, respectively. The anode efficiencies at a given anode voltage are about a factor of 1.2 higher for Xenon operation, which is in acceptable agreement with the theoretical estimate from above.

VI. Helicon Thruster

A helicon plasma thruster is based on a helicon plasma source specifically designed to provide high plasmas– exhaust velocity.

A helicon thruster is composed by few physical elements:

- A feeding system able to provide the required neutral gas flow;
- A glass tube where the plasma is generated;
- An antenna having helix shape wrapping the glass tube;
- A system of coils or permanent magnets placed coaxial with the glass tube to yield a magnetic field able to confine the plasma and to increase power deposition of the antenna;
- An additional system of coils for the magnetic nozzle.

The thrust is obtained by exhausting the plasma into vacuum upon driving it through a suitable magnetic field whose gradient is optimized to increase plasma velocity.

Plasma acceleration appears to be due to two main mechanisms: (i) plasma expansion into a magnetic nozzle [15,16], (ii) plasma acceleration through a potential drop which, under some circumstances, builds up on the exhaust zone [17-20].

In this paper is considered the helicon plasma thruster under development in the frame of the HPH.com program funded by the European Commission.

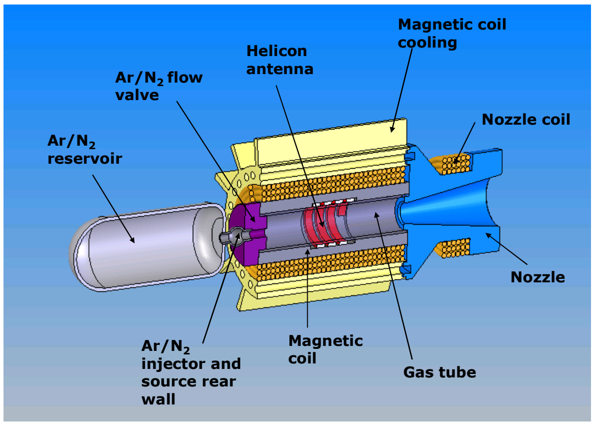

Figure 8 Scheme of HPH.com helicon thruster

HPH.com is a double mode helicon based plasma thruster. The first mode is high efficiency low thrust on which the thruster operates in the pure plasma mode, the second (COMBI) is an high-thrust low-efficiency mode on which plasma is used to heat or decompose a secondary propellant. Expected performance range of HPH.com, powered at 50 W are: thrust ranges involved is around 2 mN, with a specific impulse of 1500s. the mass and volume are around respectively 1.5 kg and 1l. Propellant considered in HPH.com is Argon. Regarding the hydrazine mode the thrust range is between 4 and 27 mN and a specific impulse of 200 s with a power input of 35 W.

Summarizing the combined system allows to obtain a flexible system that can achieve several propulsion tasks: it permits a low thrust at high specific impulse and a high thrust at low specific impulse.

a. Helicon plasma thruster operation with different propellants.

Helicon sources have been already used with a wide variety of different gasses (SF6, CF4, SiH4, CH4, H2, and O2) for industrial processes [21]. Helicon sources look particularly suitable for operation with different gases thanks to their intrinsic characteristic of being electrodeless and having a confining magnetic field, which provide low erosion even with reactive gases.

The presence of the Double Layer (DL) in helicon plasma sources has already been evidenced for a variety of gases (i.e. Argon, Hydrogen, Xenon, Oxygen, Nitrogen, Methane, Ammonia (NH3), Nitrous oxide etc.) [22-27]. DL has also been studied in electronegative gases by Plihon [25] showing strong differences respect to electropositive argon DL [26].

In most of the experiment and under many different conditions the plasma exhaust velocity has been in the promising range of 10-20 km/s. However, a simple prediction of the specific impulse is still difficult since it is influenced by different factors, such as (i) the amount of wave deposited energy that is converted into available internal energy, (ii) the details of the electron distribution function, such as the presence of a hot-electron tail, (iii) the two-dimensional character of the plasma supersonic expansion in the magnetic nozzle, (iv) the ion magnetization, and (v) the magnetic detachment mechanism. Thus, both the development of theoretical models and simulation codes, beyond the state of the art, is considered fundamental to design and build a competitive helicon plasma thruster.

b. Expected update of theoretical model and codes respect to HPH.com

There are several plasma processes inside the discharge tube: ionization, heating, wall losses, and formation of the plasma flow. For a monoatomic propellant, these processes can be studied with both fluid and particle formulations. For a non monoatomic propellant, the variety of processes and ion species make the fluid formulation less suitable. Propellant decomposition and ionization can be studied first with a 0D (global) model. This would estimate whether full ionization is achieved and the average plasma internal energy. A more detailed study, unveiling the spatial structure of the several plasma processes inside the tube (production, heating, and flow) is afforded better with a particle-based formulation, that will yield the behavior of the different ion species, than with a macroscopic formulation, which would suffer from being either too simplified or little tractable. All of these codes need to be extended by inclusion of all the relevant cross sections of the propellants.

The plasma-wave interaction process involves mainly the electrons, with a minor role of ions. Therefore it should not be much affected by the type of ions, except of course for the coupling with the plasma dynamics inside the discharge tube. This includes the determination of the electron distribution function.

Power coupling and plasma evolution within the source is studied in HPH.com through combined codes: (i) electromagnetic code, solving Maxwell equations, (ii) particle codes solving particle motion within the source [28]. Particle codes include Montecarlo collisions. These codes can run with multispecies ions and calculate electron distribution function. However they need all the relevant cross section of the propellant under investigation.

Acceleration of the weakly-collisional plasma in the magnetic nozzle and the eventual detachment are in principle affordable with both particle-based and macroscopic formulations, for any propellant. For a monoatomic propellant, fluid models under progress cover both the 1D axial acceleration (including the possible formation of a double layer) and the 2D features of the expansion. The extension of these fluid models to non mono-atomic propellants would take into account the different acceleration of the several ion species and their partial contribution to self-determine the ambipolar electric potential.

c. Experimental set-up to test HPH.com with gas mixtures

HPH.com experiment is currently tested in two different type of facility, inside (at ONERA) and outside (at CISAS and KhAI) a vacuum chamber [29]. In the following list it is provided a list of diagnostics applied with indicated, if required, the expected update, in case of operation with different propellant gases:

(i) Microwave interferometer: to achieve an accurate measurement of the integral of the plasma density along the interferometer cord. Operation of Microwave interferometer is influenced by electron density thus it can be applied also in case of different gasses.
(ii) A radial moveable Langmuir probe, which will be used to scan the density profile (at the same axial location of the interferometer), to provide, in combination with the interferometer, an accurate measure of the plasma density on a specific axial location. In case of multiple ion-species interpretation of I-V characteristic may become very difficult. However, it can be applied to identify the radial plasma electron density profile looking at the electron-side of the I-V characteristic at different positions.
(iii) Spectrometers: Several spectrometers will be located at different positions of the experiment: three in same axial position to investigate radial plasma evolution, three on different axial position to investigate axial evolution of plasmas. Spectrometers will provide measurements of plasma density, electron temperature, and neutral density and information on the electron distribution function in the source. Data from spectrometers need to be analyzed though suitable collisional radiative model which needs to be developed for the specific propellant used.

(iv) CCD cameras will be used to identify plasma non-uniformities along the beam and along the source. CCD cameras need to be updated just with new filters related to the propellant used.

(v) Magnetic probes: two types of magnetic probes will be mounted on the experiment, a 2-axial Hall probes to measure the static magnetic field generated by coils or permanent magnet, and coils to measure the magnetic axial and azimuthal component of the electromagnetic field generated by the antenna. Magnetic probes do not need updates.

(vi) A bi-conic antenna, which will be placed close to the experiment to analyze the electromagnetic field generated by the antenna. This diagnostic does not need updates.

(vii) A current-voltage probe will be applied close to the antenna and close to the RF amplifier to measure active and reactive RF power and to identify power losses along electrical connections. This diagnostic does not needs update.

(viii) A Retarding Potential Analyzer (RPA) will be placed on the plasma beam to characterize the ion distribution function. Ion energy distribution function can be retrieved with no updates if single species ions are present. In case of multiple species ions a suitable model need to be considered to analyze data.

(ix) A Mass flow control measurement unit will provide measure and control of the neutral gas flow rate. Mass flow control device need to be calibrated for the new propellant

(x) A Vacuum gauge will measure the neutral pressure upstream the source. Vacuum gauge need to be checked for operation with different propellant.

(xi) Thrust balance (at ONERA only). Thrust balance does not need any upgrade.

(xii) LIF (at ONERA only) to measure ion vectors in the thruster exhaust. LIF need to be updated with different model and possible new lenses and lasers depending on the type of propellant to be used.

The diagnostic set-up is also equipped with a radial moveable robotic arm placed in the plasma source region, and a 3D robotic arm placed in the main vacuum chamber, which will allow axial measurement of plasma parameters.

The whole experiment is managed through a dedicated management system which will control the robotic arm, will provide trigger signals to equipment and will collect data from different diagnostics.

VII. TESTING PROBLEMATICS WITH ALTERNATIVE PROPELLANTS

In consequence of the large use of Xenon as propellant for EP thrusters, the pumping systems of the existing Vacuum Test Facilities are mainly designed to pump down this noble gas. Cryopumps are usually employed in order to guarantee a clean and high vacuum level. However, for R&D purposes, oil diffusion pumps can also be a choice.

Commercial cryopumps operates on the principle of the condensation of the working gases on cryocooled surfaces.

The vapor pressure-temperature relationship of the different gases determines the surface temperature of the cryopanels required to maintain a suitable low pressure in the vacuum chamber (Figure 9). In the practice, the temperature of the cryopanels is chosen so as the vapor pressure of the concerned gases is at least one decade lower than the required final chamber pressure.

Light gases like H_2 and Helium, as well as Neon are practically impossible to keep in a cryoncondensate status. This is the reason why special activated charcoals are employed in commercial cryopumps in order to cryoabsorb those components and guarantee an adequate pumping capability over the full spectrum of the environment gases.

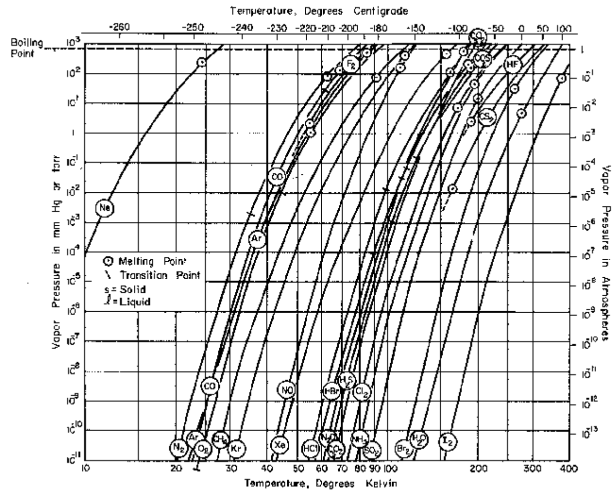

Figure 9 Vapor pressure -temperature relationship curves for common vacuum system gases [30]

The EP test facilities presently engaged in industrial development and qualification activities usually operates special cryopumping systems designed to pump efficiently Xenon propellant at ultimate pressures down to $1x10^{-7}$ mbar. To this purposes, the cryopanels temperature is set in a range of 45-50K so as the Xe vapor pressure is enough better than $1x10^{-8}$ mbar.

At that level of cryopanel temperature, the vapor pressure of Krypton stays in a range of 10^{-4} - 10^{-7} mbar.

That value is obviously inadequate to guarantee a realistic vacuum environment. Therefore, working with gases different from Xenon will require a re-design and upgrade of the existing cryopumping systems. In a simple case, smaller cryopanels cooled by single-stage cryorefrigerators will provide the lower temperature required to pump efficiently the alternative propellants (30-35K for Krypton). However, this reduction in size of the crypanels will have an impact on the overall pumping speed of the facility and therefore on the dynamic vacuum performance.

The situation will be even worse in case of EP operations with O_2, Argon and N_2 (e.g. for RAM-EP testing), for which very low temperature cryopanels will be required (in the order of 20 – 25 K).

In this regard commercial double stage cryopumps operating in an enough large range of temperatures are probably the best solution to achieve the objective of a clean and high pumping capability of different propellants.

For research purposes, oil diffusion pumps offer a suitable pumping speed over the largest spectrum of propellants.

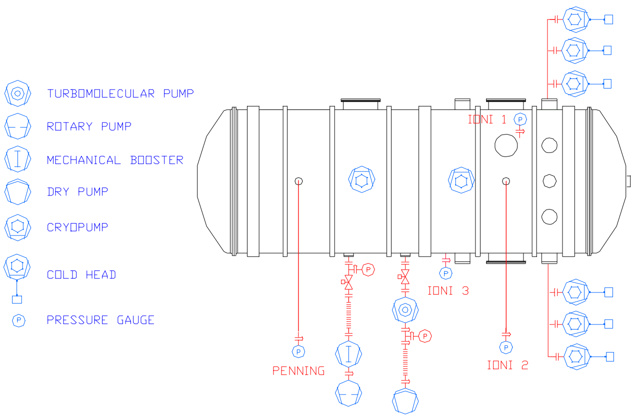

Figure 10 AEROSPAZIO' s LVTF-1 test facility pumps arrangement [31]

The LVTF-1 test facility at Aerospazio, was designed since the beginning in order to provide good pumping capabilities also for air. The existing cryogenic system consist of a combination of commercial cryopumps and special custom made cryopanels and provide more than 100.000 l/s pumping speed on Nitrogen gas.

VIII. Conclusions

In order to evaluate the possibility to reduce the dependency of the European space industry from Xenon high cost and its non predictable fluctuation an assessment of the possibility to use existing consolidated electric propulsion technologies with other noble gases has been performed. Ion thrusters demonstrated an increase in specific impulse but a not negligible increment in transfer time for standard commercial missions. This is not a drawback for scientific space exploration missions where the advantage of the higher Isp and the possibility to reduce to less than 1% the efficiency gap with Xenon easily allow to consider Krypton propulsion as a valuable candidate for a trade off. Regarding commercial missions which typically require lower specific impulse levels between 1500s and 3000s, Hall thrusters demonstrated an efficiency gap of about 15% that may be reduced with better understanding of the Krypton ions dynamic inside the thruster and increasing the anode flow rate.

Similar results have been obtained in course of development studies on the novel HEMP Thruster concept. Operation of the HEMPT DM8 laboratory model DM8, which was optimized to middle to high specific impulse operation with Xenon, has shown that thrust and specific impulse essentially can be maintained on the costs of an about 20% higher input power to the thruster when operated with Krypton instead of Xenon. Helicon thruster, although still under development, looks very suitable to operate with different propellant and their mixture thanks to their intrinsic low sensitivity to erosion and high versatility to many different operational conditions

Therefore as a next step it is proposed to perform a study on space craft and mission level to investigate the trade-off between cost reductions on the propellant and reductions in thrust or an increase in power demand of the electric propulsion system. Finally a study of the result of using propellants composed of conveniently selected mixtures, aiming the increase of the thrust may also be conducted.

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