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Prospects for the use of helicon thrusters for space exploration.

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Abstract

The helicon wave phenomenon was first experimentally discovered in the middle of the last century. However, the theoretical description of plasma processes was given by F. Chen only in 1985. The main advantage of space propulsion based on this phenomenon is the absence of electrodes directly in contact with the plasma, which lengthens the propulsion system's lifetime and decreases production costs. The aim of the studies described in the paper was to assess the prospects for using helicon thruster in various space missions. The main problem while designing modern helicon thrusters is their low efficiency. In this paper, an attempt has been made at assessing the ways the energy is lost in helicon thrusters, and ways have been identified to reduce these losses. In order to estimate the losses, FEM analysis has been conducted, existing models studied, and losses for various undesired processes calculated. As a result of the analysis of the obtained data, the main disadvantages and principal engineering challenges of this type of thrusters were outlined. In the course of the research, a comparison was made with other types of electric propulsion in the context of the requirements of missions featuring constellation maneuvering, LEO to GEO orbit-raising, as well as deep space missions.

1. Introduction

The effect of inciting helicon waves in plasma was discovered in 1960s. A helicon wade is an underdamped cross wave incited in plasma in the presence of an external magnetic field with the inductivity values satisfying the following inequation:

$$\omega_{Li} \ll \omega \ll \Omega_e \ll \omega_{Le} \ ,$$

where ω is the operating frequency, ω_{Li} is ionic Langmuir frequency, Ωe – Electron cyclotron resonance frequency, ωLe is Langmuir frequency.

This process features a high concentration of plasma of up to 1e19 m^{-3}[1,2]. Today, helicon thrusters for space applications are developed actively [3-6].

The key idea behind the basic outline of a helicon thruster (see fig. 1) is the extraction of quasi-neutral plasma. Resulting from the fact that the initiation of the discharge and the following acceleration of the plasma volume is conducted without using electrodes, there is no direct contact of the plasma with the conductive elements of the thruster. This allows using virtually any gas as a propellant and extends the thruster's lifetime greatly. The only source of energy for such a device is an RF generator connected to the inductor (in case of using permanent magnets). The absence of the neutralizer an auxiliary power supplies makes this thruster a very interesting device. However, the modern prototypes of helicon thrusters demonstrate a very low efficiency of no more than 20% [7], which limits their usage in spacecraft.

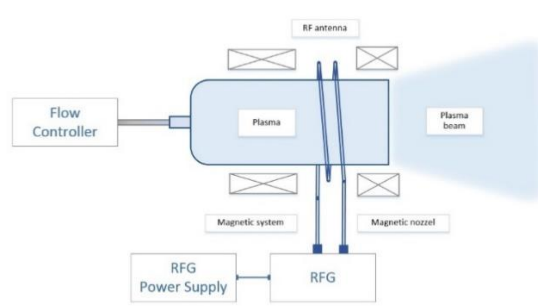

Figure 1 - basic outline of a helicon thruster

It is well known, that in mission planning they normally care about maneuvering speed (defined by thrust), and the amount of propellant required (defined by the specific impulse). Therefore, in order to assess the technical perfection of a device, we propose using an efficiency value including a complex of parameters of the thruster's performance. It is also important to mention that the problem of maintaining the thermal balance of the spacecraft is defined by the amount of dissipated heat, and for that reason the efficiency of the thruster has a key role in designing the whole spacecraft.

In this paper, an attempt has been made at estimating the values of losses of various types in helicon thrusters, assessing the prospects of using this scheme, and suggesting ways of improving it.

Types of processes and the method of assessing their efficiency

Below, a suggested method for assessing the efficiency of various processes in the helicon thruster system is summarized.

The existing experimental data on the existing helicon thruster prototypes are a result of a complex of factors, therefore, for a correct analysis of the reasons for the low efficiency it is necessary to account for not only plasma effects, but also others, connected with power feed systems being not ideal, parasite processes of inciting eddy currents and magnetic reversal. It is worth mentioning that, for example, in [8], a suggestion is mentioned that the primary reason behind the low efficiency of helicon thrusters are ohmic losses in the feed lines.

As the system consumes power, the following processes occur:

1) Power supply system energy transfer:
    a. Skin-effect in the conductive elements
    b. Dielectric losses in the insulation
    c. Ohmic losses in electronic components
2) Parasite EM connections to the structure:
    a. Eddy currents in metallic elements
    b. Magnetic reversal in magnetic materials
    c. Dielectric losses in dielectric materials
3) Power consumption by the plasma (for ionization and accompanying processes)
4) Conversion of the total kinetic energy of the ions into the directed motion energy

Defining the corresponding coefficients for estimating the mentioned processes we shall, firstly, consider the efficiency of the power supply system,

$$k_{RFG} = \frac{W_{in}}{W_{total}}$$

where W_{in} – output power of the matching network (or a resonant RF generator)

W_{total} - total consumed power

The power on the inductor contacts that is spent on maintaining the helicon charge and on parasitic EM connections mentioned above:

$$W_{in} = W_{EC} + W_{pl}$$

where W_{EC} – power for parasitic EM connections, W_{pl} –absorbed power.

$$k_{EC} = \frac{W_{EC}}{W_{pl}}$$

k_{EC} – percentage of the losses for parasitic EM connections.

For assessing the efficiency of a chosen thruster outline let us define the following coefficients describing the efficiency of passing the energy of the EM field to the ions k_d, the efficiency of extracting the excited ions k_{out} and the quality of beam focusing:

$$k_d = \frac{W_\Sigma}{W_{pl}}$$

where W_Σ - The total power of thermal motion of the ions.

$$k_{out} = \frac{W_{out}}{W_\Sigma}$$

where W_{out} - The power of the particles, leaving through the exit.

$$k_n = \frac{W_{out}}{W_{beam}}$$

where k_n – magnetic nozzle efficiency, W_{beam} – beam power.

Thus, the full efficiency of the system is:

$$\kappa_{tot} = \kappa_{RFG} \cdot (1 - \kappa_{EC}) \cdot k_d \cdot k_{out} \cdot k_n$$

To estimate these values, corresponding calculations and reviews were done. Let us examine each of the processes thoroughly and determine approximate values of those coefficients

3. Power Supply System Losses

As it normally is in lab conditions, a power supply system for a helicon thruster features an industrial RF generator, a coaxial feed line and a matching network. The purpose of the latter is to correct the impedance of the load at the end of the line to the value of the RF generator's output resistance and the wave impedance of the feed line. A typical wave impedance for industrial RF generators is 50 Ohm. The full output power, which is a metric in many experiments, is measured by the generator's internal means, and often, when analytical and experimental data are compared, the matching unit losses are not accounted for. These losses comprise dielectric losses in matching capacitors, active resistance losses of the matching inductance coil, and losses in the connecting cables. According to [9] at 13.56 MHz frequency these losses together may reach up to 10% of the power depending on the operating mode and the structure of the feed. It is shown in [10] that a value of k of 0.9-0.98 is usual for modern devices.

In the context of analyzing the efficiency of onboard power supply, it is worth mentioning that the efficiency of the RF generator itself can vary depending on the principle of the generator's operation and the quality of its implementation. Generators for lab usage mostly use AB or B-class amplifiers. The efficiency of such devices is 50-70% [11], which limits using such topology for onboard systems. However, the recent development of semiconductors allowed for resonant RF generators. For such devices, the efficiency κ_{RFG} can reach 95%, which makes it a promising solution for onboard systems.

A resonant RF generator with a D-class amplifier was developed by the authors of the paper for the GT-50 propulsion system for small satellites (fig. 2). A prototype of the generator measures 100x100x115mm in size and works within the frequency range of 1-6 MHz at up to 120W of power. The efficiency of the device reaches 95% (see fig. 3) [12].

Figure 2 - the RF generator prototype for GT-50 propulsion system

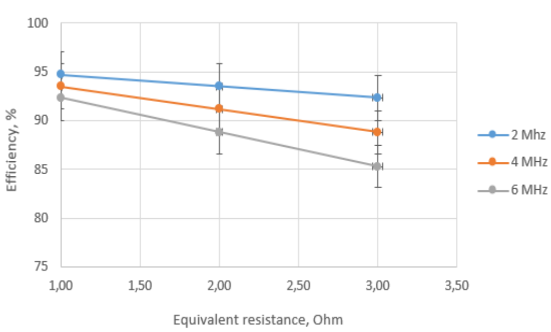

Figure 3 - the RFG efficiency at 120 W output power [12]

Similar devices are in development in many research groups in the world, and they create opportunities for developing compact and efficient power supply systems for helicon thrusters. As for the limits for the parameters in the devices of the mentioned type, it could be noted that for D-class amplifiers the operating frequency is limited to several MHz due to the switching losses. For E-class amplifiers the allowed frequencies can reach hundreds of MHz, because of the zero-current and zero-voltage switching. At the same time, a D-class amplifier allows varying the operating frequency in a broad range, and E-class amplifiers only work in a narrow frequency band.

It is known that as the frequency grows, the losses on the conductive elements increase, as well as the dielectric losses in the insulation and active losses in the components. Thus, with increasing the operating frequency a problem arises of maintaining a high efficiency and thermal balance of the structure.

Concluding the section, it can be noted that the development of helicon thrusters is tied with developing power supply systems for them. The newest prototypes can provide satisfactory efficiency and, therefore, satisfactory thermal losses in the power supply system of a thruster. It is worth mentioning that increasing the operating frequency is unfavorable due to the switching losses and skin-effect losses in conductive elements.

4. Losses for Parasite EM connections to the structure

The antenna's EM field interacts with all the parts of the thruster's structure. The power losses for ohmic resistance in conductive elements and eddy currents in metallic parts that are close to each other are defined by κ_EC coefficient. It is important to note that in addition to the mentioned losses there could exist losses for magnetic reversal and dielectric losses, however the preliminary modelling showed that for classic structural layouts the values of such losses are negligible. The modelling was done using COMSOL Multiphysics software package (Magnetic and electric fields module).

After a series of calculations for the selected thruster configuration, it was revealed that the inductance and resistance of the inductor do not depend on the current amplitude, but depend only on its frequency and the presence of surrounding metal parts. As a result of the simulation, the dependences of the resistance of the isolated inductor and the thruster assembly as a whole on the RF generator frequency were determined.

In order to estimate the κ_{EC} coefficient, a series of calculations was done for thruster structures described in [5] and [13].

In the Takahashi thruster permanent magnets are included, mounted as shown in fig. 4. This configuration ensures that there are no closed loops around the inductor, which significantly reduces losses for eddy currents.

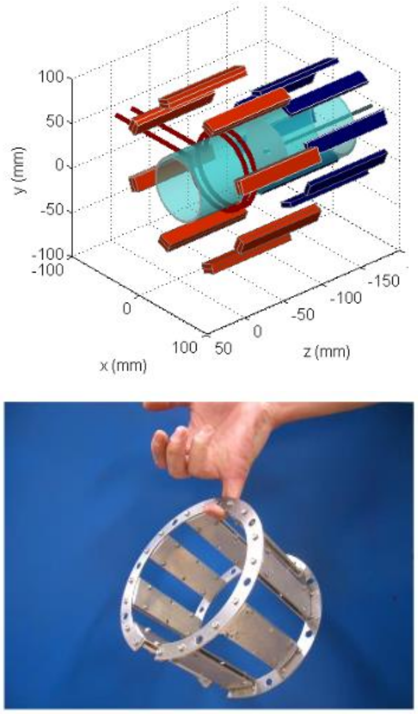

Figure 4 - A scheme of permanent magnets in the Takahashi layout

The permanent magnets in this structure are mounted in aluminum holders. In the considered frequency range of 6-80 MHz the skin-layer's thickness is less than 0.1 mm, therefore the aluminum serves as a screening shield for the permanent magnets. Summarizing, one can note that significant losses of this type can only be seen in the inductor and in the magnet holders. In fig. 5, the results are shown of estimating the equivalent resistance of the system for the described case (the inductor is represented only by 2 coils, with no direct connections to the RF generator).

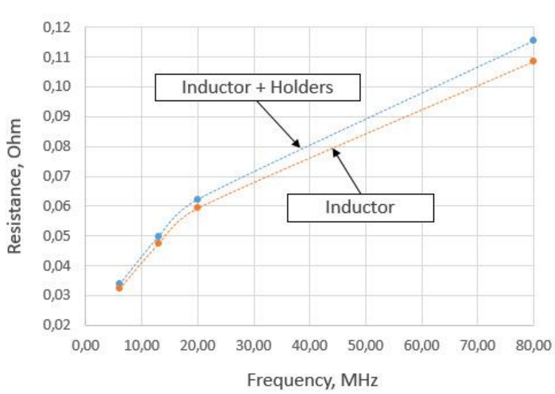

Figure 5 - Equivalent resistance of the system

It is easy to see that the losses in the aluminium holder are insignificant compared to the losses in the inductor itself.

To estimate the amount of losses in the system one can address [14]. In case of 1000 W consumption the total equivalent resistance of the inductor and the plasma lies between 0.8-3.5 Ohm, which corresponds to a value of the current in the inductor of 17-35 A. To estimate the power spent on ohmic resistance end eddy currents the following equation is used:

$$P = I^2 R$$

where I is the current, and R is the equivalent resistance.

In this way, the power losses at 13 MHz will be 14-61 W, which corresponds to k_{EC} of 1.5- 6.1 %. It is necessary to take into account the fact that reducing the consumed power leads to the increase in the percentage of these losses in the system, however, in the considered outline at 600-1000 W the parasite connection losses do not exceed 10% at 13 MHz.

To estimate the need for the complex structure as the one the Takahashi team uses, it was decided to run the calculations for other type of thruster structure employing classic electromagnets (shown in fig. Figure 6) [13]. It was discovered that the aluminum structure holding the electromagnets serves as a shield for them. The losses in this configuration at 13 MHz frequency are 26% more than for the previous case. It is worth mentioning that the structural layout of this thruster features a significant gap (20 mm) between the inductor and the conductive elements, and this solution allows to decrease the losses for eddy currents.

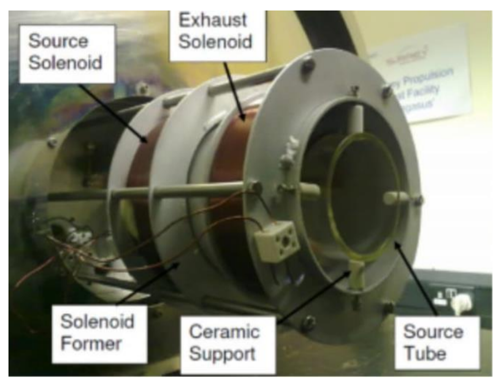

Figure 6 - Helicon Double Layer (HDLT) Thruster

One can note that in all the calculations it was assumed that the length of the connecting lines is negligible, while in [8] an assumption has been made that it is in these connectors the most significant losses are seen.

To estimate the ohmic losses in the connecting cables a model was created featuring a coaxial cable with parameters identical to those shown in [8]. The hardware implementation of the described scheme is shown in fig. 7.

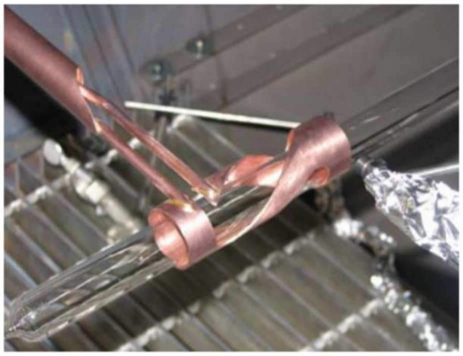

Figure 7 - Detail of the vacuum feed through and helicon antenna

For the calculations, the following parameters were chosen:

- Material: copper
- External tube diameter: 30 mm
- Internal tube diameter: 10 mm
- Wall thickness: 0.5 mm
- Temperature: 25 °C
- AC frequency: 13 MHz

It was determined as a result, that 1 meter of such cable has a resistance of 0.04 Ohm, which is comparable to the resistance of the whole structure without these connectors. Reducing the cable diameter leads to increasing the losses it introduces, meaning that it is recommended to use the shortest cables possible with big outer diameter.

Summarizing, one could note that in modern helicon thruster prototypes the losses for parasite EM connections are no more than 15%, which is however true only if a set of design requirements is met: the structure is made mainly of dielectrics, the distance between the conductive elements and the inductor is significant (no less than 2 cm), for connecting the antenna coaxial cables with big outer diameter are used, the distance between the RF outputs and the inductor is small. These losses can be mitigated by applying conductive coatings of silver on the conducting elemets and optimizing the structure's geometry. Another approach to reducing these losses might be maintaining the plasma parameters in a way that its equivalent resistance would greatly exceed the resistance of the conductive elements.

5. Assessment of Plasma Processes and Extraction

Because of the fact that every research group designs its ion source for different purposes (thruster for spacecraft [3-6], technological device [15-17]), and in every option a different configuration is considered rarely similar to that of the other groups, it is hard to analyze and compare existing variations of helicon thrusters. The most thorough studies concerning helicon thruster operating in different modes [5, 18, 19] were conducted by Takahashi group, and the results of these works were used in the present work.

The classic scheme was considered with a single magnet near the exit of the thruster, the RF generator frequency was 13.56 MHz, argon flow of 24 sccm (0.72 mg/s).

However, in the papers different values for the field near the exit is shown, as well as configuration of the magnetic field, thus the estimation of the efficiencies is qualitative.

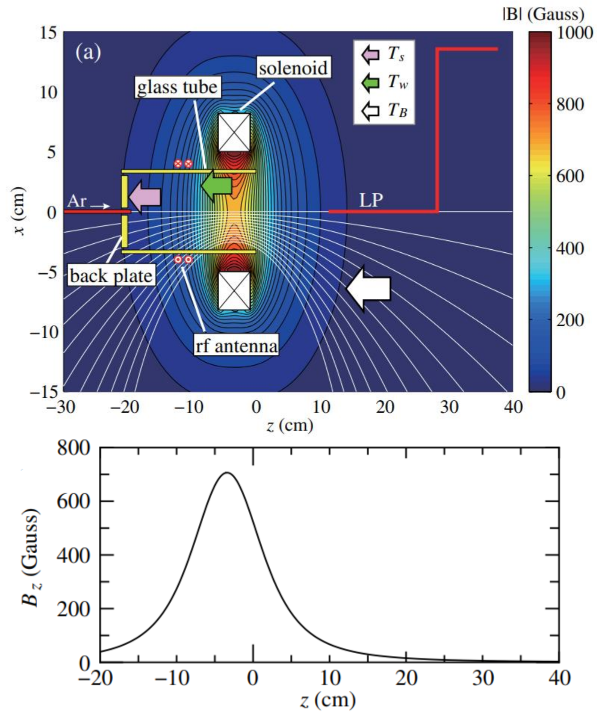

Figure 8 - Takahashi's layout (1 kW RF power) [19]

The comparison of plasma and thruster parameters is shown in Table 1. The axial distribution of the parameters in external magnetic field is uneven, therefore, mean values in the discharge chamber at the exit were considered.

Table 1. Comparison of helicon thruster parameters

RF power, N	500	600	1000
Concentration, cm^{-3}	1e12	1.5e12	1.7e12
T_e, eV	4	4	6
Thrust, mN	4	5	8
W_Σ, W	259	389	809

W_{out}, W	29	44	91
W_{beam}, W	11	17	44
k_{pl}, %	52	65	81
k_{out}, %	11	11	11
k_n, %	38	39	48
k_{tot},%	2.2	2.8	4.4

Using concentrations of the plasma and electron energy, one can estimate the power of the flow of the ions towards the chamber walls and at the exit, simplified in a form of 1d-distribution of the parameters in the volume of the discharge chamber. The distribution of the magnetic field in the chamber implies that only 20% of the particles move across the magnetic field. Roughly one can suggest, that the most of the flow is on the surfaces without the influence of the magnetic field, and for that the area considered in the analysis is set to 80% of the area of the discharge chamber cylinder.

The velocity of the particles leaving the quasi-neutral volume of the plasma is defined by Bohm velocity:

$$u_{Bohm} = \sqrt{\frac{k_b Te}{M}}$$

The total power of thermal motion of the ions towards the chamber walls and the exit is defined by the following equation [10], where $\varphi_{wall} \approx 5.8 \cdot T_e$:

$$W_{\Sigma} = I_{\Sigma} \cdot (\varphi_{wall} + 0.5T_e)$$

The ion current thus is

$$I_{\Sigma} = I_{wall} + I_{out} = 0.6\, q \cdot n \cdot u_{Bohm} \cdot (S_{wall} + S_{out})$$

The power of the particles, leaving through the exit:

$$W_{out} = I_{out} \cdot (\varphi_{wall} + 0.5T_e)$$

Because the thrust was measured by the thrust-measuring device, the power of the plume is defined, which is the power of the ion flow after the magnetic nozzle [11]:

$$W_{beam} = \frac{T^2}{2\dot{m}}$$

where $\dot{m}$ – propellant mass flow.

For simplification, a complex coefficient may be defined:

$$\kappa_{pl} = \kappa_{RFG} \cdot (1 - \kappa_{EC}) \cdot k_d$$

According to the acquired data, as the power coupling increases, the concentration and the temperature of the particles raise, as well as the efficiency of the discharge. However, only a small part (around 10%) of the discharge power goes out from the exit in the plume. Due to the fact that the magnetic nozzle is unideal, finally, only a small part of the consumed power is transferred to the directed motion of the plasma plume. The total efficiency of the thruster increases with increasing the power: for 1 kW, for example, the total efficiency is 4.4%.

6. On the Demand for Thrusters in future missions

It is a very well-known trend nowadays that the number of satellites launched annually will increase drastically over the next several years. This is mainly attributed to the announced mega constellations [g1], some of which already have several dozen satellites tested in orbit. Such constellations, of which the SpaceX's Starlink telecommunication system is the brightest representative, are by no means limited to the projects mentioned in [22]. With the new technologies emerging, there are now talks about bigger constellations in order to improve revisiting time in earth observation, new GNSS efforts, and even more exotic propositions such as advertising in space by using multiple light-reflecting satellites to form a pixelated image [23]. Some works suggest business model for using satellite systems as a backhaul for providing 5G mobile services in some remote areas [24]. There is also a trend in GEO platforms featuring electric propulsion instead of classical chemical one in order to save a certain amount of mass at launch.

For assessing a possible demand for a propulsion technology one must take into account several factors. For many applications, such as GEO platforms, the raw amount of thrust plays the key role. The thrust per Watt is even less important here, because the satellites in question are normally highly energy-efficient and do the orbit raising with the payload shut down. On the other hand, when applying the electric propulsion systems to mega constellations, one can see that they're all about saving mass and volume and prolonging the lifetime, which can for many missions now exceed 10 years. In this case, delta-V requirements, and, subsequently, specific impulse plays a major role. In deep space missions the delta-V is even more important, together with the thrust efficiency (thrust per Watt), because the power aspect in deep space missions is more of a concern than for near-Earth ones.

In addition, one must also take into account that the propulsion system is not only a set of parameters and a bunch of propellant, but a hardware solution, which features auxiliary mass, complicated subsystems, and dissipates power.

These observations are summarized neatly in [25], where the author analyzed the mass efficiency for different types of thrusters depending on the application in terms of thrust and total impulse requirements. As a result, a plot has been acquired that shows on a Thrust vs. delta-V plane regions where various thrusters are more favorable than the others in terms of mass and power efficiency (fig. 9).

It is to be noted, that in [25] several facts were not taken into account, including the price and availability of a particular solution, or whether one with given parameters exist at all. For example, there are no solutions on the market for 10N ion thrusters, however, they are still in the comparison via a set of models used to extrapolate the data on existing solutions. These hypothetical solutions, however, are not to be seen on the graph, because they unsurprisingly lose to chemical propulsion everywhere.

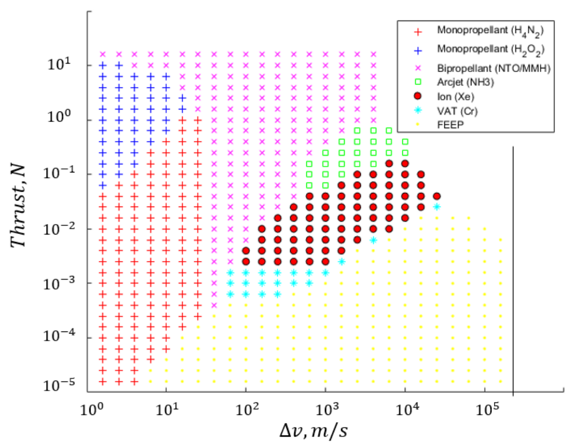

Figure 9 - The most efficient propulsion for different thrusts and delta-Vs

For the mentioned purposes, namely the constellations, swarms, next-gen deep space missions, etc., with all due considerations, the most marketable area would be in the range of 100-2000 m/s of required delta-V, and most certainly no more than 5000 m/s with satellites going through extensive maneuvering after launch (such as, for example, described in [26]).

In the thrust levels of 10-100 mN this region is almost exclusively dominated by ion propulsion. Many existing solutions already on the market have proven that this technology is very promising and is ensured a place in many future missions. However, for the bigger thrusts, where [25] identifies a slight advantage of arcjets, of which there are not too many on the market, there's a kind of a niche for a possible solution, given that it would be efficient in terms of energy usage.

Thus, there's a region somewhere near the top-right corner of the graph where there are very high delta-V requirements and big thrust, and they are almost exclusively deep-space missions. As such missions tend to have more radical solutions for the power problem (such as nuclear power supplies), the low power efficiency of helicon thrusters might be granted a pass in these missions, given, of course, that it is not ridiculously low, as is the case with early prototypes described in this paper. However, if the helicon thrusters are set to compete with existing ion propulsion systems in near-Earth application, they still have a very long way to go towards higher efficiency.

7. On the Demand for Thrusters in future missions

The analysis shows that the main reason of the helicon thruster's low efficiency is the absence of a suitable mechanism for extracting the ions out of the discharge chamber. Thus, up to 90% of the energy collected by ions is wasted for their collisions with the walls not improving the beam power. Optimization of the structure, creating a sophisticated magnetic nozzle can't change the performance significantly. In addition, rising the magnetic field for reducing wall losses led to unadvisable structure changes which can limit its application on spacecraft. Therefore, existing prototypes of helicon thruster developed in accordance with the basic scheme are more like plasma sources than thrusters in general.

Even today, there exist hybrid solutions for helicon thrusters, in which an effective helicon discharge is used as a first stage for creating plasma, which is then accelerated in the second stage of the thrusters by various means: with ICR-antenna (VASIMR), ordinary nozzle (HPH plasma thruster), rotating magnetic field (RMF concept), and with classic ion-optical electrostatic scheme (GT-50 ion thruster).

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