Development of a High Power Electrodeless Thruster

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Abstract: The Elwing Company is currently developing of a high power (10-20 kW) electrodeless thruster. Specific adaptations of the basic design have been investigated to combine the characteristics required for long steady state operations at thrust level in excess of 2 N for total power of less than 20kW. These improvements are related to all sections of the propulsion system from gas injection to power coupling, to magnetic configuration & thermal management. The specific challenges of high power steady state operations are outlined and the engineering solution retained fully exposed.

Nomenclature

B	=	magnetic field
E	=	electric field
F	=	accelerating force
I	=	electrical current intensity
I_{sp}	=	specific impulse
m	=	particle mass
m_e	=	electron mass
n	=	plasma particle density
n_e	=	plasma electron density
Ψ	=	ponderomotive potential
q	=	electrical charge of a particle
v_c	=	cyclotronic velocity of a particle in a magnetic field
ε_0	=	vacuum electrical permittivity
μ	=	adiabatic invariant or magnetic momentum of a charged particle in a magnetic field
ω	=	applied electromagnetic field pulsation or angular frequency
Ω_c	=	particle cyclotronic pulsation or angular frequency in a magnetic field
ω_p	=	plasma pulsation or angular frequency

I. Introduction

OPENNING the possibility to perform highly energetic missions, such as large spacecraft orbit raising in short delays or fast trip to outer planets, with electric propulsion systems requires the availability of high power EP thrusters. The Elwing Company designed its electric propulsion system aiming to provide larger thrust density

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than already available solutions. This characteristic along with its electrodeless acceleration stage and capability to be extensively throttled in thrust, power and specific impulse, seems to make it especially appropriate for this type of missions.

Even if the basic electrodeless thruster design can accommodate large power without any modification, this design can be made more efficient by taking into account the various specific challenges implied by continuous, high thrust, high power operations. For instance, it has been found useful to reduce the distance between the microwave power source and the thruster to avoid breakdown inside transmission lines.

Similarly the magnetic field generating structure and the overall mechanical structure have to be conceived to make sure that the plasma density will not shield out the microwave. From the few options considered for the magnetic structure design, the permanent magnet-based option has been retained and the field configuration produced will be explained. As the magnetic field topology and the operating microwave frequency are linked, C to X band microwave have exhibited a good tradeoff between device size, thrust density and total thrust.

Processing large power in small devices can create thermal loads unseen at lower power. Many processes, such as radiative and convective transfer from the plasma, are involved in the generation of heat in the propulsion system at high power which call for both fundamental solutions, for example limiting power transmitted to the plasma in the ionization region, and technical solutions, e.g. regenerative cooling at high mass flow rate.

An important part of the work is focused on the design of microwave power coupling devices, as these parts play a key role in the efficiency of the system. An example of retained cavities design will be exposed. Finally, 3D simulations of the fields generated by the structure retained allowed computing performance projections using a numerical fluid model.

II. General Overview of the Electrodeless Plasma Thruster Concept & Structure

The Elwing Company has developed a new type of plasma thruster which would not be subject to thrust density limitations, such as can be observed in plasma thruster in which plasma velocity is increased by the action of a static electric field. This original concept relies on the ponderomotive force to accelerate the plasma flow. We will first review briefly the characteristics of the ponderomotive force. Then we will explain how this force can be used in a plasma thruster and we will outline the general structure of the electrodeless plasma thruster concept created by Elwing.

A. The Ponderomotive Force Characteristics

The ponderomotive force is created by gradient of electromagnetic energy density[1]. On a single particle and without any static magnetic field, the ponderomotive force can be expressed by Eq. (1).

$$\vec{F} = -\frac{q^2}{4m\omega^2}\vec{\nabla}E^2 \tag{1}$$

Which, for a plasma, can be rewritten as in Eq. (2) by using plasma frequency (expressed in Eq. (3))

$$\vec{F} = -\frac{\omega_p^2}{2\omega^2}\vec{\nabla}\frac{\varepsilon_0 E^2}{2} \tag{2}$$

$$\omega_p^2 = \frac{n_e e^2}{m\varepsilon_0} \tag{3}$$

This force can also be expressed as deriving from the potential expressed in Eq. (4).

$$\Psi = \frac{\omega_p^2}{2\omega^2}\frac{\varepsilon_0 E^2}{2} \tag{4}$$

The effect of the ponderomotive force is that in a region of electromagnetic energy density gradient the plasma is pushed toward areas of lower electromagnetic energy density (Fig. 1). The ponderomotive force is applied on both ions & electrons and all particles are accelerated in the same direction. The force intensity is much stronger on electrons than on ions; nevertheless, as electrons are accelerated more intensely, and tend to gain higher velocity than ions, they create a strong ambipolar field which equalizes both species drift speed.

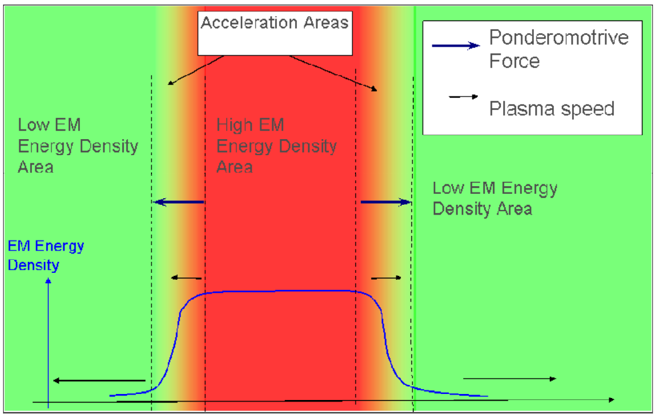

Figure 1. Schematic field topology of ponderomotive force created by a high energy density area. *The ponderomotive force is proportional to EM energy density gradient. The symmetry of the high energy density area creates two areas of strong gradient of opposite directions.*

A very simple plasma thruster could be created by generating a plasma in an area of high energy density located upstream from a strong energy density gradient[2]. The plasma speed increases as the plasma stream progresses along the energy density gradient. Nonetheless, such a simple arrangement only uses one gradient, whereas in most cases a high energy density area will be surrounded by gradients, which in a linear device usually translates into two gradient of opposite signs or directions. Using both gradients would greatly enhance the efficiency of any device based on this accelerating force as long as a mean is found to use both "sides" of the gradients to increase the speed in one fixed direction.

The presence of a static magnetic field modifies the ponderomotive potential (Eq. (5)) by introducing a new term of difference between the local cyclotronic frequency (Eq. (6)) and the frequency of the applied electromagnetic field.

$$\Psi = \frac{\omega_p^2}{2\omega(\omega - \Omega_c)}\frac{\varepsilon_0 E^2}{2} + \mu B \tag{5}$$

$$\Omega_c = \frac{qB}{m} \tag{6}$$

In turn, the applied force is modified and can be split in three terms (Eq. (7)), one very similar to the unmagnetized ponderomotive force(Eq. (8)), another force term (Eq. (9)) similar to the so-called "µ-grad B" force existing in non uniform magnetic field and a third term (Eq. (10)) proportional to both magnetic field gradient and electromagnetic energy density.

$$\vec{F} = \vec{F}_{\nabla B-like} + \vec{F}_{Unmagnetied-like} + \vec{F}_{cross} \quad (7)$$

$$\vec{F}_{Unmagnetized-like} = -\frac{\omega_p^2}{2\omega(\omega-\Omega_c)}\vec{\nabla}\frac{\varepsilon_0 E^2}{2} \quad (8)$$

$$\vec{F}_{\nabla B-like} = -\mu\vec{\nabla}B \quad (9)$$

$$\vec{F}_{cross\nabla} = -\frac{\omega_p^2}{2\omega(\omega-\Omega_c)^2}\frac{\varepsilon_0 E^2}{2}\vec{\nabla}\Omega_c \quad (10)$$

While the "μ-grad B-like" component does not add much energy as it merely converts a part of the cyclotronic impulse into axial impulse. The term appearing under the effect of crossed energy density gradient and magnetostatic gradient is strong only where the difference between cyclotronic frequency and applied electromagnetic field frequency is small as decrease as the inverse of the square of this difference. Furthermore, the direction of this force is only governed by the gradient of the magnetic field thru the cyclotronic frequency. The last term, similar to the unmagnetized ponderomotive force, is noticeably modified by the introduction of a term of frequency difference between the electromagnetic field and the cyclotronic frequency.

Interestingly the sign of this term, hence the direction of the force, is modified by the sign of this difference. If a uniform static magnetic field is applied, both the "μ-grad B-like" and "cross gradient" terms disappears unlike the third term which will be redirected by the sign of the frequencies difference. Whereas, if the applied electromagnetic field frequency is higher than the cyclotronic frequency, the ponderomotive force will accumulate the plasma in areas of lower energy density, in the opposite case the ponderomotive force will push the plasma towards the area of higher energy density. This effect can be used in a plasma thruster to accelerate the plasma flow in the same directions on both "sides" of an area of higher energy density.

It should be noted that, as the force is considerably stronger on the electron, the electron cyclotron frequency is the one which should be used in the evaluation of the frequency. Similarly, as most of the plasma inertia comes from the ions, the ions mass should be used in the final evaluation of the ponderomotive force intensity. Another important fact is that the ponderomotive force is strong as the gradient of commonly obtained field intensity for RF or microwave can easily reach values larger than 200V/cm^2. Similarly, and unlike most other plasma accelerating processes, the ponderomotive force increase with the plasma density. In fact, this effect can be reduced by skin effect if the used frequency becomes lower than the plasma frequency. Nevertheless, as long as plasma thickness is of the same order of magnitude as the skin depth, the increase of ponderomotive force intensity with plasma density dominates the skin effect shielding.

B. General Outline of the Electrodeless Plasma Thruster

As exposed in the previous section, the magnetized ponderomotive force can be leveraged in a plasma accelerator by using appropriate electromagnetic field topology. Specifically, for the accelerating force to have the same direction on both sides of an area of high energy density we have found that on the upstream side of the area the local electron cyclotron frequency must be larger than the applied field frequency while on the downstream side the electron cyclotron frequency must be smaller than the applied frequency. This arrangement, illustrated in Fig. 2, implies a static magnetic field presenting a decreasing intensity along the main axis in the flow direction.

Hence we can outline the overall characteristics of an electrodeless plasma thruster using ponderomotive acceleration stage as follow. The electrodeless thruster requires a structure generating a localized intense electromagnetic field featuring steep gradients toward surrounding areas where no field is applied. The electrodeless thruster would also requires a structure generating a static axial magnetic. The magnetic field should be such that the local electron cyclotron frequency is greater than the applied field frequency on the upstream side area of energy density gradient and lower than that of the applied field on the downstream area of energy density gradient. Ideally, an ionization structure should provide a low temperature, dense, low speed plasma to the upstream side of the acceleration structure. Last, the electrodeless thruster needs a mechanical structure able to support and ensure the geometrical stability of each of the components, especially able to withstand launch vibration and thermal expansion during in-space use.

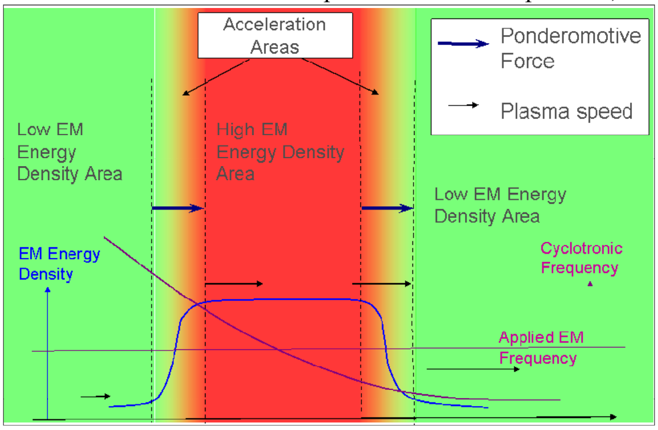

Figure 2. Schematic field topology of magnetized ponderomotive force created by a high energy density area with static magnetic field. *The reversal of the sign of the difference between applied field frequency and local cyclotron frequency allows for the magnetized ponderomotive force to have the same direction on both areas of EM energy density gradients.*

A simple solution to fulfill these requirements is exposed in Fig. 3. One of the most effective ways of creating an intense and localized high energy density area is to use resonators as they naturally create intense gradients on the sides of a high energy density area. Further, resonators strongly increase EM fields intensity, even when they contain a highly dissipative load. The magnetic field is generated here by coils around the thruster axis. In this simple design the axial magnetic field is also used to enhance the efficiency of the ionization structure, by creating a non perfect magnetic bottle around the ionization area. This magnetic bottle can increase the efficiency of an ECR ionization structure[3] by lengthening the path of electrons thus increasing the probability that electrons energized by the ECR field would undergo ionizing collision before entering the accelerating structure and becoming "lost" for ionization. The ECR field is applied by a cavity to increase the energizing field intensity which in turn improves the coupling efficiency.

This overall thruster design provide numerous advantages such as complete absence of electrodes and more generally of any material part in direct contact with the plasma thus ensuring altogether very low erosion and contamination, ability to use any propellant even chemically aggressive and reduced thermal loads on the thruster structure. Furthermore, combining an efficient ionization stage and an acceleration stage able to increase velocity of dense plasma beam, such a thruster design allows reaching thrust density in excess of $100 N/m^2$. Last, to a large extent, a given thruster can operate under broadly different power and mass flow rate conditions.

Nevertheless, the simple structure outlined here can be refined and especially adapted for large power. The specific challenges and adaptations for high power use will now be exposed.

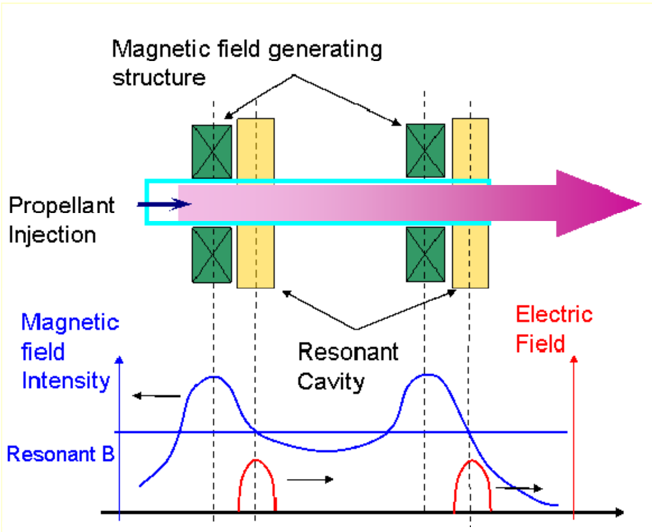

Figure 3. Overview of the basic structure of the electrodeless thruster. *The magnetic structure creates an axial magnetic field featuring a magnetic bottle and a diverging field suitable for ponderomotive force acceleration.*

III. Design of High Power Electrodeless Plasma Thruster

Most other electric propulsion devices are constrained to operate under stringent plasma density limitations. This plasma density limitation implies that to operate at higher power, and to deliver more thrust, these devices dimensions must be increased. On the other hand, the performances of the electrodeless plasma thruster scales favorably with applied power and plasma density. Moreover the magnetic field topology contributes to the confinement of the plasma electrons. These characteristics imply that the physical dimensions of the electrodeless plasma thruster are not directly affected by the power level of the device. We will now review in details what are the phenomenon occurring when the electrodeless plasma thruster is operated at higher power and we will expose some specific structural modifications conceived to enhance the efficiency of the device at high power.

A. High Power Challenges

While the power level of the device has no direct influence on the device dimensions, increasing the power fed to either the acceleration or the ionization stage can transform otherwise negligible plasma phenomenon into important limitations. First, we want to clarify that we designate by "high power" operations, operation of the thruster at high power and high thrust level. Of course, with an electrodeless plasma thruster, high power operation can allow either a "high thrust mode" or a "high specific impulse mode". While it is true that increasing the specific impulse for a given mass flow rate will result in increasing the thrust, it should be noted that doubling the thrust by this mean requires multiplying by a factor 4 the power applied to the acceleration stage. Moreover, in electrodeless plasma thruster, increasing the specific impulse does not present any type of specific challenges as demonstrated during tests exhibiting the capability to accelerate Hydrogen ions at velocity in excess of 1000 km/s.

The very first phenomenon to be noticed when increasing the plasma density to increase the thrust is a decrease of plasma skin depth. The decreasing skin depth is due to the increase of plasma conductivity with its density. The reduction of skin depth increases the absorption of the EM fields at the plasma border thus reducing their intensities at the plasma beam core. As the skin depth is also decrease with increasing applied field frequency, this phenomenon impact might be limited by using lower frequency.

Similarly the thermal management of the device becomes more complicated as the plasma density is increased. Denser plasma is a stronger source of radiation implying an increasingly efficient radiative transfer of heat from the plasma to the device material walls. In turn this stronger irradiation of the walls could lead to more important vaporization of their material, even if the order of magnitude remains much smaller than what can be witnessed during direct ion impact on other devices walls. This radiative transfer can be limited by increasing the dimension of the plasma chamber. Last, it should be noticed that the plasma is in a relatively "cold" state in the whole device except after the acceleration stage where it actually leaves the device so this phenomenon has a limited impact.

In the same way, a denser plasma could impose a larger flux of electrons and ions altogether to the device wall. In the electrodeless plasma thruster the extent of this phenomenon is limited by the presence of an axial magnetic field which efficiently "insulates" the plasma from the device wall. This confinement can be further improved by various means such as increasing the dimension of the device, the magnetic field intensity or applying a magnetic field radial gradient by multipolar magnets. Nevertheless it is noticeable that it seems that the plasma diffusion to the wall is the most important single factor limiting the plasma density at high power as these diffusion losses increases non-linearly with ionization power.

Last, at high power, the design of the waveguide and resonant cavities have to be carefully studied to avoid breakdown in these component when transmitting large power. Similarly the design of the chamber at high power should integrate materials selected for their low dielectric tangent at frequency of use. For instance much of these problems can be eliminated by revising the design to ensure an efficient coupling of the microwave power to the plasma, as all losses are a sign of structure mismatch.

B. Overview of High Power Electrodeless Plasma Thruster Design.

As explained above, it has been found that operating at lower frequency strongly limits the potential negative effects of increasing the plasma density at high power to produce more thrust. Even through the frequency used is the primary dimensioning parameter of the electrodeless plasma thruster, such a shift does not increase considerably the dimension of the overall devices.

In order to ensure a more uniform application of the microwave power to the plasma beam as well as keeping the control of the resonance mode of the cavity when the plasma density increase, high power cavities have been designed which allow in a compact devices the development of an extended stationary wave (Fig. 4). Such a complex cavity can accommodate widely different plasma conditions without changing resonance mode and field pattern. In the high power devices all components coupling are performed by using apertures to avoid arcing often observed with loops or dipole coupling. This accelerating cavity can either be fed directly by a powerful microwave source or with a multiple smaller sources under certain conditions.

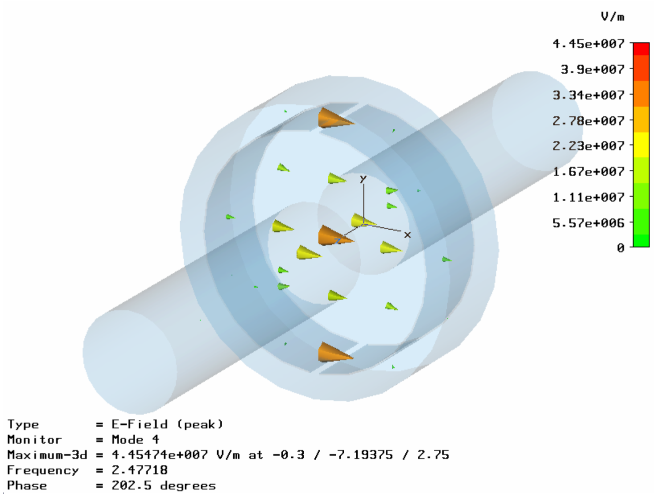

Figure 4. Schematic representation of the resonant electric field in a complex cavity. *The cavity structure creates an expanded elaborate stationary field which is less sensitive to variation of the central plasma physical properties.*

Reducing the operating frequency also allows using a smaller and lighter magnetic field generating structure, as the magnetic field intensity varies linearly with applied field frequency. The reduced magnetic field intensity could suggest the use of coils, nevertheless it was found that the need to magnetize larger volume of plasma justified relying on permanent magnets. The actual setup of permanent magnet requires extensive simulations to closely reproduce the topology created by using coils (Fig. 5). The permanent magnet and electromagnets design requires a precise thermal management of the overall magnetic field generating structure to prevent the magnet from approaching Currie temperature. Passive protection, casing of high thermal conductivity, can easily be planned but often not required as thermally insulating the structure from the plasma is not challenging.

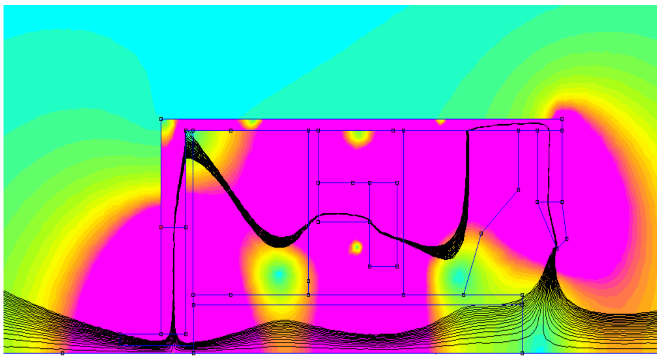

Figure 5. Schematic representation of the static magnetic field topology. *The magnetic field profile is projected on an axial plane, the axis of thruster is represented by the bottom frame of the picture. The intensity of the field is indicated by the colors of the areas (pink for intense field, blue for weak field and yellow for intermediate values). A few magnetic field line of interest for the plasma beam behavior are also represented.*

During the development of the high power electrodeless plasma thruster, we discovered that the propellant injection can influence the performance and specifically the temperature of the plasma wall along in the ionization structure. The performances are improved if the injection of propellant is precisely located within the closed magnetic field lines.

All of these design improvements have been incorporated in the design (outlined in Fig. 6). The resulting device is a compact cylindrical object of foot print dimensions between 10 cm x 10 cm x 20 cm and 15 cm x 15 cm x 30 cm (without the microwave sources) and dry weight of 4-8 kg for units able to withstand 6-15kW of microwave power (i.e. 10-20kW of bus power). The projected performances calculated from a simple simulation code of these designs are presented below.

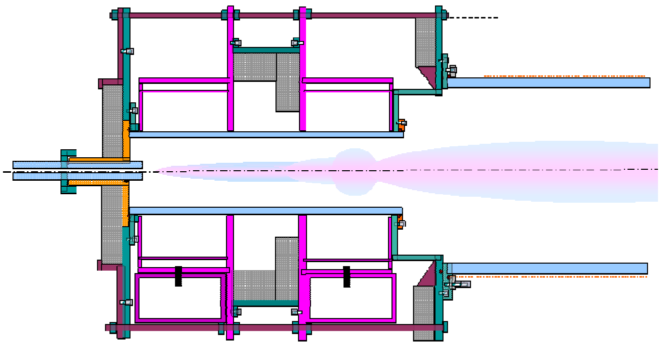

Figure 6. Schematic overview of the high power electrodeless plasma thruster structure. *Axial cut schematic overview of the thruster. The propellant is injected on the left side of this figure, ionized by the first resonator and accelerated by the magnetized ponderomotive force created by the second resonator. The light blue/purple shape represents the approximate plasma beam profile.*

C. High Power Electrodeless Plasma Thruster Potential Performances.

The plasma beam behavior has been numerically modeled by a simple fluid, bi-dimensional, axisymetric, steady state code. This code only provides a statistical approach of the ionization stage and the ponderomotive force and potential is averaged to smooth the discontinuity of potential near the ECR plane.

Even, if this code is rather crude, the results produced are consistent across various structures tested and follow the intuition (efficiency quickly decreases at low power, is higher in “high specific impulse mode” than in “high thrust mode” for any given power…). The results produced can be summarized as such. A thruster using 7mg/s of Xenon, 340W for the ionization stage, 7120W for the acceleration stage at 2.45GHz produce 315mN of thrust at a specific impulse of 4800s in “high specific impulse mode”. Similarly, using 19mg/s of Xenon, 950W for ionization stage and 7100W for acceleration stage at 9 GHz, produce 510mN of thrust at a specific impulse of 2650s. Similarly using approximately 10kW of microwave power, the electrodeless plasma thruster produce a force of 870mN at specific impulse around 1700s for a mass flow rate of 55mg/s, or even larger than 1200mN for specific impulse of about 1000s, in “high thrust mode”. We can infer from the results available that for 15kW of power the electrodeless plasma thruster would deliver over 2000mN of thrust at a specific impulse of approximately 1020s.

A more complete 3D fluid code is currently under development to provide a deeper understanding of the intricacy of the actual fields operating in the electrodeless plasma thruster.

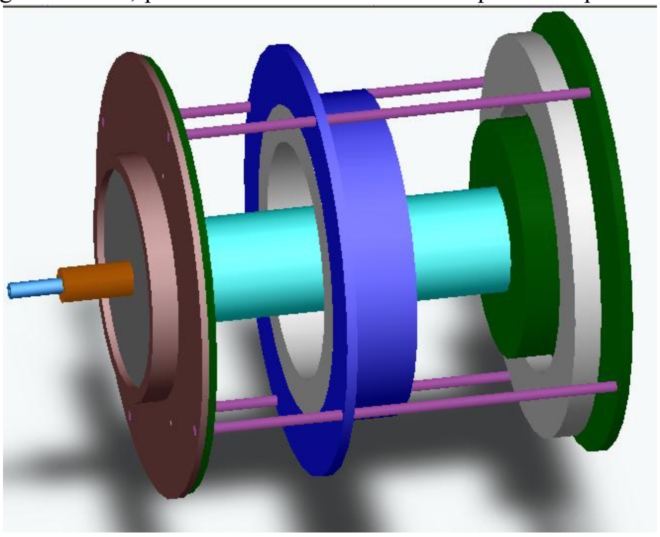

Figure 7. Schematic 3D view of high power electrodeless plasma thruster structure. *The resonators are not represented to allow optical access to the main plasma chamber.*

IV. Conclusion

The development work performed to adapt the electrodeless plasma thruster basic design to both low power and to high power showed that, with the exception of micropropulsion, the electrodeless plasma thruster technology can be applied to address various spacecraft motion needs from attitude control to highly energetic mission.

The Elwing Company is currently evaluating the accuracy of the model previsions against the on-going performance tests of the various configurations of the thruster, namely middle power (1200W-2600W), High power (nominal of 15kW) and sub-kilowatt demonstrators. Once these experimental performances and scaling laws will be validated, the demonstrators will be submitted to lifetime tests to confirm the stability of the performances over time.

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