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Double-Sided Ion Thruster for Contactless Space Debris Removal

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ABSTRACT: LEOSWEEP mission proposes to de-orbit a 1.5-ton launcher upper stage from a nearly polar Low Earth Orbit (LEO) in 170 days using the Ion Beam Shepherd (IBS) method proposed by Bombardelli. The IBS method is a contactless space debris removal concept where the momentum to the debris is imparted by high-energy collimated neutralized plasma beam produced by the Impulse Transfer Thruster (ITT). To compensate for the thrust produced by the IT thruster, a second Impulse Compensation Thruster (ICT) is also required. The LEOSWEEP project team plans to use a radio-frequency (RF) thruster for the IT due to its capability to produce a low divergence beam, which was shown to greatly increase the momentum transfer efficiency. Nevertheless, the most optimum thruster option for the IC has not been chosen yet. In this paper, we propose a novel thruster concept for the LEOSWEEP mission where, instead of the proposed two-thruster design, a single double-sided thruster simultaneously producing two ion beams is used. The beam from one side of the thruster is used for the IT, while the beam from another side is employed for IC. The advantage of such a design is that it requires two times less RF power than two single-ended thrusters. Additionally, it is expected that such a system would have a much simpler sub-system architecture, lower cost, and lower total mass. The double-sided thruster has been designed using the computational tools developed by the authors. It was shown that the screen voltage of 3 kV results in the lowest total power. Simulations indicate that the thruster should be comparable if optimized, to a system of two single-sided RF ion thrusters that need around 2.5 kW of power and approximately 30 kg of fuel for the duration of the LEOSWEEP mission. The thruster is currently being built with the testing campaign expected to start shortly.

1. INTRODUCTION

It is estimated that there is around 6000 tons and 15,000 trackable debris objects in the orbit [1]. Bombardelli et al [1] have proposed an Ion Beam Shepherd (IBS) concept that involves using a highly collimated neutralized plasma beam produced by the Impulse Transfer Thruster (ITT) aimed at debris in order to de-orbit it [1, 2]. A second Impulse Compensation Thruster (ICT) is also required to compensate for the thrust produced by the ITT and to match the satellite and debris orbits. The European commission has financed a project under a name LEOSWEEP ("Improving Low Earth Orbit Security with Enhanced Electric Propulsion") that aims to demonstrate the first active space debris removal mission of a Ukrainian rocket upper-stage using the IBS method [3].

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The mission requires that the thrust delivered to the target is more than 30 mN and the total power of both thrusters is no more than 3 kW [4]. Currently, it is planned to use a radio-frequency (RF) thruster designed as a part of the LEOSWEEP project for the IT [5] and either another RF thruster or a Hall thruster for the IC purposes. Preliminary analysis performed by the authors in [5] has showed that to achieve the mission requirements, the RF thruster must work with a beam voltage of around 3.5 kV and have a beam divergence of roughly 6 degrees. The IC thruster is not required to have such a low beam divergence angle and thus can work with much lower beam voltages.

Such a two-thruster design greatly increases the cost, weight, and complexity of the satellite. To solve these issues, we present a novel ion thruster concept for the IBS type missions where, instead of two initially proposed thrusters, we use only one thruster capable of generating two distinct ion beams for IT and IC purposes. The proposed thruster uses RF waves generated by a multi-turn coil to produce plasma inside a ceramic discharge chamber. At both ends of the discharge chamber there are different grid systems specially designed for IT and IC purposes.

The IT ion optics system incorporates a grid design that generates a flat, low-divergence beam, but at the same time has a low beam power. Since the IC side does not have strict requirements on the beam divergence, it is optimized for thrust compensation and satellite orbit control. For a constant RF power and propellant flow rate, the thrust magnitude produced by each set of grids is controlled by changing the screen grid voltage. This is because the plasma potential is common to both ion extraction systems. To independently control the thrust produced by the IT and IC sides, the number of apertures in the ion optics is adjusted. Additionally, the thrust magnitude can also be manipulated by varying the negative grid voltages and thus changing the plasma meniscus shape.

The double-sided ion thruster has been designed and optimized using computational tools described in [6]. In performing the optimization, the coil geometry and discharge chamber dimensions were varied with the goal to reduce the total power and propellant flow rate required to fulfill the mission requirements. The optimization analysis was also performed on the screen grid voltage. Modeling shows that the thruster performance is comparable to that of two standalone RF ion thrusters with an advantage of a much simpler and lighter sub-system architecture. The thruster has been manufactured and is currently being assembled with the testing phase planned to start shortly.

2. CONTACTLESS SPACE DEBRIS REMOVAL CONCEPT

The Ion Beam Shepherd (IBS) concept is depicted in Fig. 1. As the figure illustrates, the Impulse Transfer Thruster (ITT) produces a collimated quasi-neutral ion beam and generates thrust F_{ITT}. The target here represents a piece of debris that is being bombarded by high-velocity ions coming from a thruster positioned 10-20 meters away. The ions impart their momentum, thus producing a force on the debris. If enough momentum is transferred, the debris orbit decreases until it burns in the Earth's atmosphere. Such a debris removal concept is often referred to as contactless since there is no direct contact between the debris and the satellite.

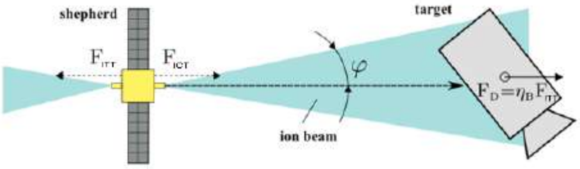

Figure 1. Schematic of the Ion Beam Shepherd (IBS) concept [1].

Not all momentum generated by the ITT is transferred to the debris. The force transferred to the debris F_D can be expressed using the momentum transfer efficiency η_B as [1,2]

$$F_D = \eta_B F_{ITT}. \tag{1}$$

The momentum transfer efficiency η_B depends on the beam divergence angle φ, target debris size and the distance between the satellite and the target. To make the concept work, a second thruster called the Impulse Compensation Thruster (ICT) has to be used to offset the thrust produced by the ITT, keeping the satellite and debris in equilibrium. If we assume that the IBS satellite and the target debris are in a circular orbit, we can calculate the force F_{ICT} that needs to be generated by the ICT as [1, 2]

$$F_{ICT} = \left(1 + \eta_B \frac{m_{IBS}}{m_{TG}}\right) F_{ITT}, \tag{2}$$

where m_{IBS} and m_{TG} are the ion beam shepherd satellite and debris target masses, respectively.

It can be shown that the minimum beam divergence angle φ achievable by the electric propulsion thruster strongly depends on the longitudinal ion velocity v_i using the following equation [7]

$$\varphi_{min} = \tan^{-1}\left(\frac{\sqrt{2q_e T_{eV}/m_i}}{v_i}\right), \tag{3}$$

where q_e is the electron charge, T_{eV} is the ion temperature in eV and m_i is the ion mass. The high velocity of ions can be obtained by having a large acceleration potential applied on the ion optics grids. However, having a high acceleration potential results in a high beam power. Therefore, an optimization analysis is necessary.

3. IBS MISSION PROPULSION SUBSYSTEM

The goal of the LEOSWEEP mission is to de-orbit a launcher upper stage weighing 1.5 tons from a nearly polar Low Earth Orbit (LEO) at 300 km in 170 days [4]. This means that the debris has to change the altitude by about 2 km per day. Tab. 1 summarizes the Electric Propulsion Subsystem (EPS) requirements needed to fulfill the mission goals.

Table 1. IBS mission EPS requirements.

EPS requirements	**Values**
Force on the debris target F_D (mN)	30
Total input power to both thrusters (kW)	2.6
Distance between the debris and ITT (m)	>7

An optimization analysis was performed by authors in [5] in order to choose the best EPS parameters to achieve the mission goals. They concluded that to keep the total thruster input power below 2.6 kW, the screen voltage must be around 3.5 kV, which would produce a beam divergence of about 6 degrees.

The LEOSWEEP project team has decided to use an RF ion thruster for the IT. The main components and the working principles of the RF thruster are depicted in Fig. 2. The thruster consists of an insulating gas chamber wrapped around with a coil. The coil is connected to an RF generator (RFG) that produces a high-frequency oscillating electromagnetic field E. Inert gas (usually Xenon) flows at a constant rate into the discharge chamber and upon applying power to the RFG, the free electrons naturally present in the gas are accelerated in a random-manner mechanism by following the alternating electric field. When these electrons gain enough energy, they ionize the neutral gas to produce the plasma. The plasma generated in the discharge chamber floats with respect to the walls at a few tens of volts. In order to extract and accelerate the ions from the plasma, a negative bias potential is applied to the extraction grids located at one end of the chamber. The acceleration grids cause an ion beam current I_b to be extracted, which can be measured on the screen grid power supply.

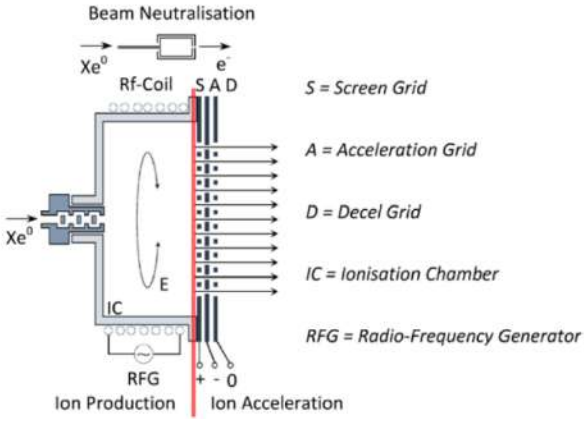

Figure 2. Schematic illustrating the main components of an RF ion thruster [8].

The energy at which the ions are accelerated mainly depends on the screen grid voltage, which we will denote as the beam voltage V_b. As described before, the beam voltage greatly influences the divergence angle of the beam. The advantage of the RF thrusters compared to other electric thrusters is that the ion production and acceleration mechanisms are separate. To produce the ions, the RFG power is transferred from the RFG to the coil and then the plasma. Whereas, to extract the ions, the beam power needs to be applied to the screen grid. This allows a very high voltage to be applied to the screen grid without the fear of inhibiting the plasma production mechanism. It should be noted that there is also an electron source installed to neutralize the positive ion beam. This prevents the thruster from reaching a high positive potential.

The ICT, on the other hand, is expected to work with much lower screen grid voltages compared to the ITT since the requirements on the beam divergence are much more relaxed. Nevertheless, to still produce enough thrust to compensate for the IT thrust, the beam current of the ICT must be much higher, which might negatively influence the total thruster input power balance. Therefore, an optimum voltage must be chosen. Authors in [5] showed that the most optimum ICT beam voltage is around 1200 V, which gives a beam divergence of 28 deg. As a result, the beam power of the ICT should be substantially lower than that of the ITT.

The list below summarizes the main performance parameters predicted for the IT thruster.

- Force on debris: 30 mN
- Distance between thruster and debris: 7 m
- Thrust: 31 mN
- Beam current: 317.7 mA
- Beam voltage: 3500 V
- Beam power: 1130 W
- Beam divergence: 6 deg.
- RFG power: 240 W
- Total ITT power: 1370 W
- Specific impulse: 5260 s.

4. NOVEL DOUBLE-SIDED ION THRUSTER CONCEPT

Main characteristics of a novel double-sided ion thruster concept are presented in Fig. 3. The thruster was developed as an alternative for the LEOSWEEP mission. Instead of the two initially proposed thrusters, one providing impulse transfer (ITT) and one compensating the impulse (ICT), we have only one thruster that shoots two ion beams from each side. The main goal is to reduce the sub-system complexity associated with a two-thruster design while having similar (or better) power and propellant requirements. An additional advantage of such a system is that the plasma is common to both extraction systems and, therefore, the RFG input power remains the same, regardless of the production of the second beam. Therefore, taking the LEOSWEEP mission as an example, a gain of around 250 W can be achieved in comparison to the two-thruster design.

The concept of shooting two ion beams from the same thruster is not entirely new. It was investigated by Collingwood in her Ph.D. thesis [9]. However, the thruster she designed was made out of two discharge chambers, two separate coils and a gas inlet through the middle. The discharge chambers were separated with a ceramic shutter. This allowed an independent control of the neutral gas and ion densities inside each discharge chamber. Therefore, the thrust could be controlled independently from each side of the thruster. However, such a design had very large plasma power losses due to a large discharge chamber surface area and complexity associated with two separate coil/chamber designs. Additionally, there were problems related to the neutral gas distribution uniformity due to a large aspect ratio of the thruster.

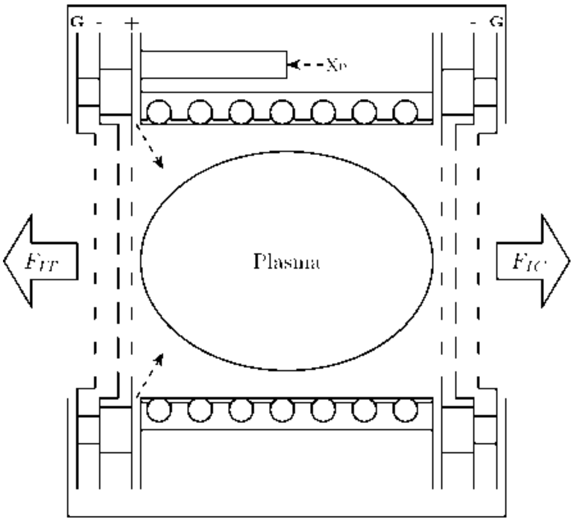

Figure 3. Double-sided ion thruster concept geometry.

A double-sided ion thruster has been designed, manufactured and is currently being assembled. The thruster has been designed and optimized for the minimum total input power and propellant consumption using the RF thruster model developed in [6]. In particular, the optimization analysis was used to determine the discharge chamber geometry and dimensions, as well as the number and spacing of turns of the RF coil. In performing the optimization analysis, the LEOSWEEP mission requirements were used as the constraints. As Fig. 3 illustrates, the designed thruster has only one 8-turn coil and one cylindrical discharge chamber, making the design efficient and compact. Therefore, the total length of the discharge chamber is similar to that of a one-sided thruster. This should significantly reduce the eddy current power losses to the coil and the plasma power losses to the discharge chamber walls.

In addition, the coil shape is supported and pressed against the discharge chamber using insulating holders. The ion optics grids are separated with ring-shaped insulators. The propellant flows into a specially designed flange on the IT side of the thruster. The propellant flow is then directed at the discharge chamber walls in order to increase the neutral gas residence time and thus the uniformity inside the discharge chamber. In addition, the thruster was designed in such a way that it could also be used to generate a very low thrust in the micro-Newton range. This was also the main objective analyzed by Collingwood in [9]. A very low net thrust can be generated by varying IT and IC side thrust values so they are nearly equal.

Finally, we hope to use the concept thruster to investigate various plasma physics phenomena.

As Fig. 3 indicates, one side of the thruster provides the impulse transfer (IT) thrust, while the other side is used to extract the impulse compensation (IC) thrust. In order to create a plasma, a power is fed to the coil using the RFG and the gas is supplied into the discharge chamber. Once the plasma is ignited, a positive potential is applied on the screen and negative potential on the acceleration grids through the BEAM and ACCEL1 power supplies, respectively as seen in Fig. 4. Since the applied beam voltage on the IT side shows up in the plasma sheath itself, it means that the same floating potential will be present on the screen grid at the IC side of the thruster. Therefore, to extract the beam from the IC side, it is enough to apply a negative voltage using the ACCEL2 power supply. However, it means that the produced thrust from each side of the thruster becomes coupled through the common beam voltage. Therefore, it becomes challenging to independently control the thrust values from the IT and IC sides of the thruster to meet the mission requirements.

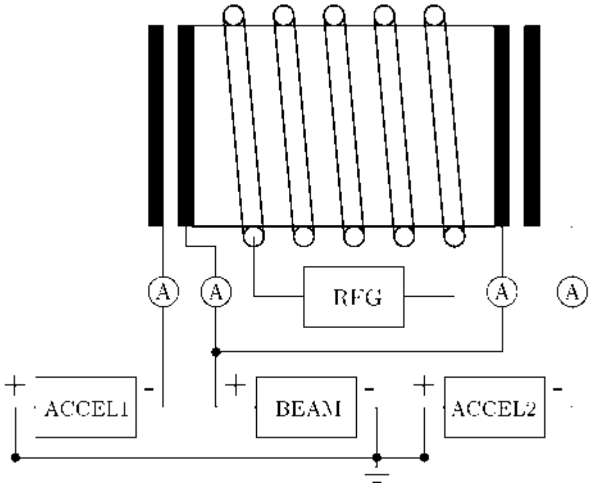

Figure 4. Double-sided ion thruster electrical circuit.

Nonetheless, the thrust produced by the IT and IC sides of the thruster can be controlled by adjusting the beam current I_b extracted from each side. The easiest way to control the beam current is by managing the number of apertures N on the IT and IC grids separately. This is because the extracted beam current I_b is proportional to the open area of the screen grid as $I_b \sim N\pi d^2/4$, where d is the aperture diameter. Another way to independently control the extracted beam currents is by modifying the plasma meniscus shape at the either end of the thruster. This can be done by varying the ACCEL1 and ACCEL2 voltages.

5. SIMULATED THRUSTER PERFORMANCE

Using the RF ion thruster performance model from [6], we simulated the double-sided thruster performance while keeping the LEOSWEEP mission requirements as inputs. First, we performed the optimization analysis in order to choose the most optimum beam voltage. Figs. 5 and 6 display how the RFG input power and beam power vary with the beam voltage.

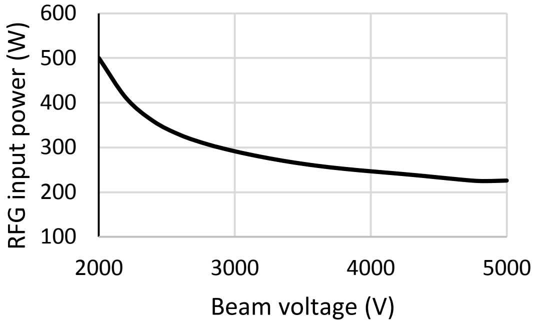

Figure 5. RFG input power variation with the beam voltage.

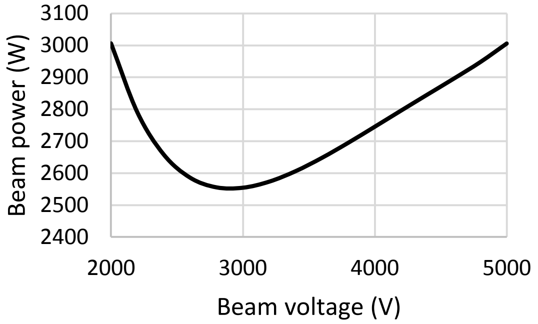

Figure 6. Beam power variation with the beam voltage.

As seen in Fig. 5, the RFG input power decreases with the beam voltage. This is because an increase in the beam voltage results in an increase in the momentum transfer efficiency η_B. This in turn, as given by Eqn. 1, decreases the IT thrust (as well as IC thrust) that needs to be generated to impart 30 mN on the debris object. Therefore, a lower beam current is needed, which results in a lower RFG power that needs to be supplied to the plasma. Fig. 6 indicates that the beam power has a minimum at around 3000 V. The reason for this is that the beam power is a product of the beam voltage and beam current. As described before, as the beam voltage increases, the required beam current decreases. However, at the beam voltages past approximately 4000 V, the momentum transfer efficiency stops increasing with the beam voltage and plateaus. As a result, the thrust that needs to be generated by the thruster T plateaus as well. Therefore, the rate at which the beam voltage V_b increases overtakes the rate at which the beam current I_B decreases since $T \sim I_B\sqrt{V_b}$, and the overall product of the two (the beam power) starts increasing.

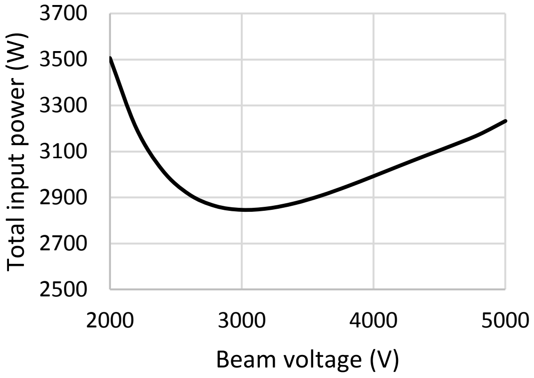

Figure 7. Total input power variation with the beam voltage.

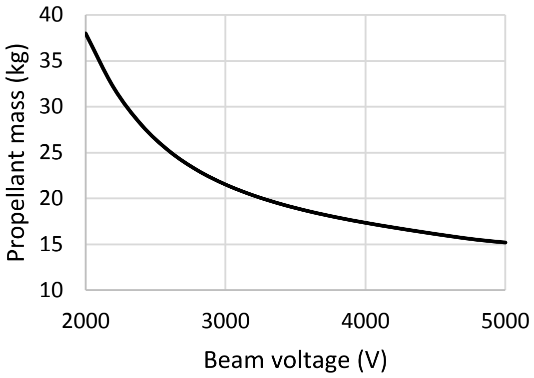

Figure 8. Total propellant mass variation with the beam voltage.

In Figs. 7 and 8 we plot how the total input power and total propellant mass needed for the LOESWEEP mission change with the beam voltage. Notice that Fig. 7 mimics the trend behavior observed in Fig. 6 since the beam power adds a much greater contribution to the total input power. As illustrated in the figure, the beam voltage that causes the minimum input power is around 3000 V. Nevertheless, the total propellant mass decreases as the beam voltage goes up due to a decreasing thrust that needs to be provided by the thruster, and thus lower beam current. Note that at 3000 V the total propellant mass is about 21 kg.

Since the double-sided thruster generates two distinct ion beams for clarity and comparison to other single-sided ion thrusters, we show the performance values for IT and IC sides separately as seen in Tab. 2. In the table we also show the performance of the single-sided ITT which we denote as LEOSWP. Note that both thrusters transfer 30 mN of force on the debris while being 7 m away. As seen in the table, the IC side has to produce 30% more thrust compared to the IT side. This requirement comes from the Eqn. 2, assuming the debris mass of 1500 kg and the satellite mass of approximately 500 kg. Note that for the double-sided thruster, the optimization analysis showed that applying 3000 V results in the lowest total power. However, for the single-sided thruster, the lowest total power occurs at 3500 V.

Table 2. Double-sided ion thruster performance as obtained from the Impulse Transfer (IT) and Impulse Compensation (IC) sides compared to the single-sided LEOSWEEP thruster.

	IT	IC	LEOSWP.
Force on debris (mN)	30		30
Distance between thruster and debris (m)	7		7
Thrust (mN)	33	43	31
Beam current (mA)	370	480	320
Beam voltage (V)	3000	3000	3500
Beam power (W)	1110	1440	1130
Beam divergence (deg.)	6	6	5
RFG power (W)	290		240
Propellant flow (sccm)	14.9		5.6
Specific impulse (s)	5205		5260

Since 30% more thrust has to be achieved from the IC side, the extracted beam current from the IC side has to be 30% higher as well. This is because the beam voltage on both IT and IC sides is the same due to the same plasma potential with respect to the ground. There are two ways to achieve 30% higher thrust from the IC side. The first method involves having 30% more apertures on the IC grid system compared to the IT grid system. The second method involves reducing the number of apertures on the IT grid system by 30%. This could simply be achieved by blocking some of the apertures with tape, for instance. It is more beneficial to use the first method since the plasma density does not need to change. However, this requires having a separate grid design with a different number of apertures for each grid system.

Since we had only the same set of grids for each side, we decided to choose the second option. Therefore, as the table indicates, the double-sided thruster needs 50 W more RFG power compared to the LEOSWEEP thruster. This is because around 30% of the apertures on the IT side of the double-sided thruster were blocked. This meant that to produce the same 30 mN of thrust by the IT side, the RFG power had to be increased in order to generate a plasma density that is around 30% higher. Finally, the table shows that the double-sided thruster needs 14.9 sccm of propellant. This is much higher than the 5.6 sccm for the LEOSWEEP thruster. However, the double-sided thruster produces two ion beams instead of one. This results in the specific impulse values of both thrusters being nearly identical.

Tab. 3 gives the main plasma parameters. The table indicates that the neutral gas pressure in the discharge chamber is 0.35 mTorr. Assuming that the chamber wall temperature is around 450 K, the neutral gas density becomes 7.5E18 $1/\mathrm{m}^3$. As mentioned before, the plasma density for the double-sided thruster had to be increased. If we look at the table we see that the double-sided thruster needs to produce a plasma density of 3.5E17 $1/\mathrm{m}^3$. Note the plasma density in the single-sided LEOSWEEP thruster is around 2.8E17 $1/\mathrm{m}^3$ [5]. The difference in the plasma densities is approximately 25%, which is similar to the predicted 30% change.

Table 3. Simulated double-sided ion thruster plasma parameters.

Neutral gas pressure (mTorr)	0.35
Neutral gas density ($1/\mathrm{m}^3$)	7.5E18
Plasma density ($1/\mathrm{m}^3$)	3.5E17
Beam current density ($\mathrm{mA}/\mathrm{mm}^2$)	70
Plasma potential	24.5
Electron temperature (eV)	4.65
Electron-neutral eff. collision freq. (MHz)	2.4
Electron-ion collision freq. (MHz)	0.56
Stochastic collision freq. (MHz)	15.9
Real part of plasma conductivity (S/m)	468
Imaginary part of plasma conductivity (S/m)	-155

It must be realized the LEOSWEEP mission requires two separate single-ended thrusters or one double-sided thruster. The IT thruster details have already been presented and discussed. However, the best thruster option for the IC purpose still has not been chosen. When choosing the thruster such aspects as the total power requirements, weight/complexity of the total system and the total propellant consumption have to be considered. In Tab. 4 we show different thruster options that could be used together with the LEOSWEEP IT thruster. We also include the double-sided ion thruster to see if it is a variable candidate. As can be observed, in terms of the lowest total power, the best IC thruster would be the SPT-70 thruster or another similar Hall thruster. However, the Hall thrusters also need the largest amount of propellant for the mission, more than two times of what would be needed for the double-sided ion thruster.

Table 4. Comparison of different propulsion systems in terms of total propellant and power consumptions to fulfill the LEOSWEEP mission goals.

ITT	ICT	Total power (W)	Total propellant mass (kg)
LEOSWP. Double-sided		2840	21
LEOSWP.	LEOSWP. [5]	2928	30
LEOSWP.	RIT 15 [10]	2531	29
LEOSWP.	SPT-70 [11]	2050	47
LEOSWP.	NEXT [12]	2350	38

Continuing our investigation we see that the cusp field gridded ion engine NEXT needs 15% more power and 20% less propellant compared to the Hall thruster. In terms of power, the double-sided ion thruster seems to use 100 W less power than a combination of two single-sided LOESWEEP IT thrusters. If double-sided thruster is compared to a combination where another RF thruster RIT 15 is used, we see that the double-sided thruster requires about 300 W more power. However, it should be noted that the double-sided ion thruster presented in this analysis has not been optimized and, as was explained earlier, does not represent the most optimum design. Also, note that this study did not take into account the total system mass. We believe that the double-sided thruster would have the lowest total system mass of any two single-sided thruster systems, giving it a clear advantage.

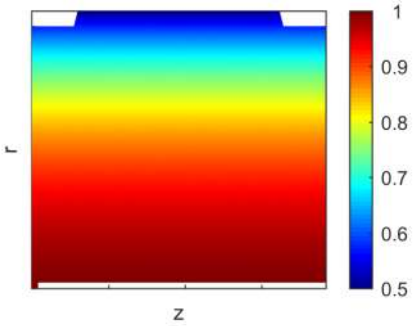

Figure 9. Plasma density distribution inside the double-sided ion thruster normalized to the center value.

To better understand how the thruster works and how it can be improved, we produced 2D field and plasma interaction plots. First, we estimate the plasma density distribution as shown in Fig. 9. As can be noticed, the normalized plasma density is maximum at the center and decays to about 0.5 at the radial edge of the discharge chamber.

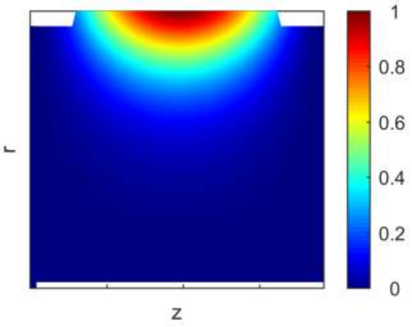

Figure 10. Electromagnetic heating inside the double-sided ion thruster normalized to the maximum value.

Using the plasma density distribution from Fig. 9 and plasma properties from Tab. 3, we plot in Fig. 10 normalized electromagnetic heating magnitude inside the plasma. As expected most of the power is transferred to the plasma next to the coil, while the power transfer to the rest of the plasma is negligible due to a finite skin depth and screening effects. Additionally, the maximum power transfer occurs in the middle of the discharge chamber due to end coil effects.

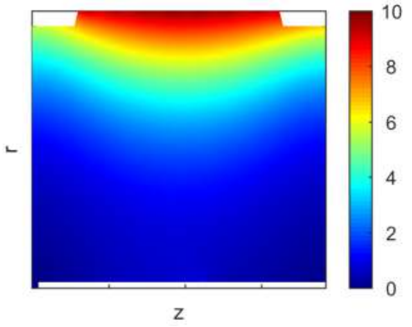

Figure 11. Magnetic field inside the double-sided ion thruster in Gauss.

Fig. 11 shows the magnetic field inside the thruster. As the figure illustrates, the maximum magnetic field is about 10 Gauss next to the coil. The field rapidly decays away from the coil, with the majority of the plasma volume being exposed to an approximately uniform magnetic field of about 2 Gauss. Finally, a current density distribution normalized to the maximum value is shown in Fig. 12. As the figure indicates, the maximum current density occurs approximately 6 mm away from the coil. This is because the plasma density increases away from the coil, while the electromagnetic heating decreases due to the screening effect.

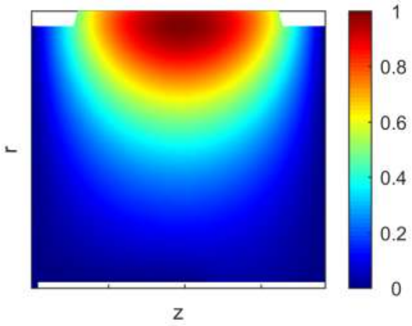

Figure 12. Current density inside the double-sided ion thruster normalized to the maximum value.

6. CONCLUSION

A double-sided ion thruster that shoots two ion beams from each end of the discharge chamber has been designed, built and is currently being assembled. The thruster has been developed to act as a candidate for the LEOSWEEP mission that aims to use the Ion Beam Shepherd (IBS) method to actively remove a debris object. The IBS concept requires to have two separate ion thrusters one for Impulse Transfer (IT) and one for Impulse Compensation (IC). The advantage of the double-sided thruster design is that it can replace the two single-sided ion thrusters with only one thruster. Therefore, it is expected that the total system cost, complexity and weight could be reduced.

The analysis has showed that the double-sided ion thruster uses 100 W less power and 9 kg less propellant than a combination of two single-sided thrusters for IT and IC purposes developed for the LEOSWEEP mission. However, compared to a system that uses the LEOSWEEP thruster for IT and a RIT15 thruster for IC, the double-sided thruster needs around 300 W more power and 8 kg less propellant. However, it should be noted that the double-sided thruster presented in this work has not been optimized due to a limited number of ion extraction grids available.

A combination of the LEOSWEEP thruster for IT and Hall SPT-70 thruster for IC seem to offer the lowest total power of the system (800 W lower than the double-sided thruster). However, the total propellant consumption is the highest at 47 kg (26 kg more than the double-sided thruster). The study excluded the total system mass analysis, where the double-sided thruster should have the lowest total mass due to its inherent simplicity compared to other two-thruster systems.

The next phase in the development of the double-sided thruster is to perform an extensive test campaign. The test campaign should take place in a newly built vacuum facility at the University of Southampton from the 24th of June to the 31st of August. The list below summarizes the main goals of the test campaign:

- Validate the proposed thruster concept
- Map the thruster performance
- Determine the optimum way to control the beam currents and thus thrusts from each side of the thruster
- Analyze the neutralizer location effects
- Determine the ways to optimize the thruster
- Perform beam and, if possible, plasma measurements

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