Impulse Transfer Thruster for an Ion Beam Shepherd Mission

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Abstract: Space debris problem is one of the most severe challenges of the modern space science and technology[1,2]. Ion Shepard concept is to be used in LEOSWEEP project as a mitigation method for the space debris problem This paper outlines the design of a Development Model thruster that is designed and constructed and is now under manufacturing and testing against major LEOSWEEP requirements. A number of design improvements were evaluated and implemented into the design of the DM thruster. This paper outlines the trade-off evaluations for different design options.

Nomenclature

RIT	=	Radio Frequency Ion Thruster
RF	=	Radio Frequency (~1MHz)
RFG	=	Radio Frequency Generator
PSCU	=	Power Supply and Control Unit
FCU	=	Flow Control Unit
F	=	Thrust
dm/dt	=	Propellant mass flow
U_{PHV}	=	Positive High Voltage
U_{NHV}	=	Negative High Volatge
P_{rfg}	=	RF Power Consumption

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I. Introduction

LEOSWEEP proposes a mitigation method for the space debris problem that currently orbits our planet. The solution proposed by LEOSWEEP is based on the Ion Beam Shepherd (IBS) concept, proposed in 2010 by the Space Dynamics Group (SDG) research team from the Polytechnic University of Madrid[3-6]. The IBS is essentially a 'contactless' actuation concept, which allows modifying the orbit and/or the attitude of a generic debris object (the 'target') using the momentum transferred to it by one or more ion beams produced by electric propulsion thrusters onboard a nearby spacecraft (the 'shepherd'), and properly pointed towards the target by means of the shepherd's attitude control.
This paper outlines the design of a Development Model thruster that is manufactured and tested against major LEOSWEEP requirements.

II. Design Considerations

A number of design improvements were evaluated and implemented into the design of the DM thruster. This paper outlines the trade-off evaluations for different design options.

Consideration was given to the following factors, weighted with reference to the importance to DM thruster development in the frame of this contract.

- Thruster Performance: the expected contribution of the design option to improved thruster performance (eg. reduced thruster power, higher propellant utilisation etc.).
- Development Risk: for example, selection of a non space-qualified part or process which would require qualification, reliability etc.
- Manufacturability: regarding ease of manufacture, manufacturing precision, lead time etc.
- Cost: manufacturing or material costs.
- Mass: the expected contribution of the design option to decreased thruster mass and increased Isp.

The most important design parameters of the thruster are thruster size and beam voltage. The thruster size determines the maximum thrust of the thruster and directly affects the discharge power consumption and the mass efficiency of the thruster.

The effect of positive high voltage (beam energy) in the thruster performance is more complicated. The beam divergence is a function of the beam voltage. A higher beam voltage will result in a lower near field divergence if accompanied by a proper ion optics, but the most important effect of the higher beam voltage is the reduction of beam divergence in far field (7m and higher). However, the higher beam voltage would lead to higher power consumption for a specific thrust or to higher power to thrust ratio. That means if the beam voltage is chosen too low, we will not be able to transfer a large part of the initial thrust to the debris and we will lose much of the thrust that we can produce for a specific amount of power. From the other side choosing a too high voltage will also reduce the value of producible thrust for a specific power. A model is developed to optimize the thruster design parameters like size and the beam voltage. The thruster design together with the first results of the test will be presented.

A. Thruster Requirements

The current specifications of the LEOSWEEP mission are summarized in [7]. The requirements for the propulsion system can be summarized as bellow:

EPS requirements and constraints Units Values
Required force on the debris, ~30mN
Operational distance between ITT and debris > 7m
Input power to the EPS PPU ~ 3kW

It is to mention that the given power is the necessary power for two thrusters. One is the impulse transfer thruster (ITT) with low beam divergence and the second one an impulse compensation thruster (ICT) which keeps the satellite in its relative position to the debris during the firing of ITT.

III. Thruster Modelling

A. Fundamentals of Radio Frequency Ion Thrusters

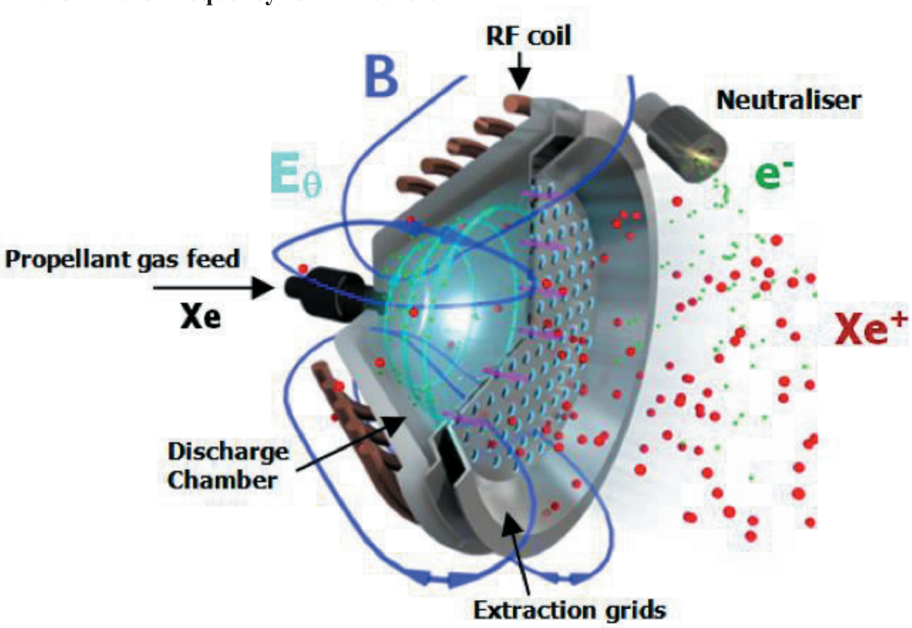

Figure 1: Operating principle of a Radio Frequency Ion Thruster[10].

B. Ionization

The discharge chamber of a radio frequency ion thruster consists of a dielectric vessel surrounded by a conducting coil (termed RF coil or induction coil) to which an oscillating current (typically at a few MHz) is applied to generate a RF field. A gas feed system supplies propellant to be ionised; typically the inert gas xenon is used but RF ion thrusters have also been operated on other propellants such as mercury, cesium, argon, nitrogen and oxygen. The RF magnetic field penetrates the vessel inducing an azimuthal electric field E□ according to Faraday's Law:

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \qquad \text{Eq. 1}$$

The induced electric field acts to accelerate free electrons present within the discharge chamber to sufficient energies for electron-impact ionizations of the neutral propellant to occur, leading to a self-sustaining discharge. No internal cathodes are required to supply electrons to maintain the discharge, as is required for Kaufman ion thrusters. A weakly ionized, non-equilibrium plasma is formed, with electron temperature considerably higher than that of the ions and neutral propellant, whose temperatures approximate that of a gas in thermal equilibrium with the walls of the discharge chamber. A stable discharge requires the power absorbed by the plasma to balance the power dissipated.

C. Ion Extraction and acceleration

The ions generated within the discharge are extracted, focused and accelerated by a set of two (sometimes three) multi-aperture grid electrodes which are biased to high potentials.

A plasma sheath forms upstream to the surface of the first grid (as depicted Figure 2), which is biased to a high positive potential typically between 1-2 kV with respect to 'ground' (or common potential of the spacecraft). This grid is often referred to as the screen grid. The second grid is located in close proximity to the first and is termed the accelerator grid.

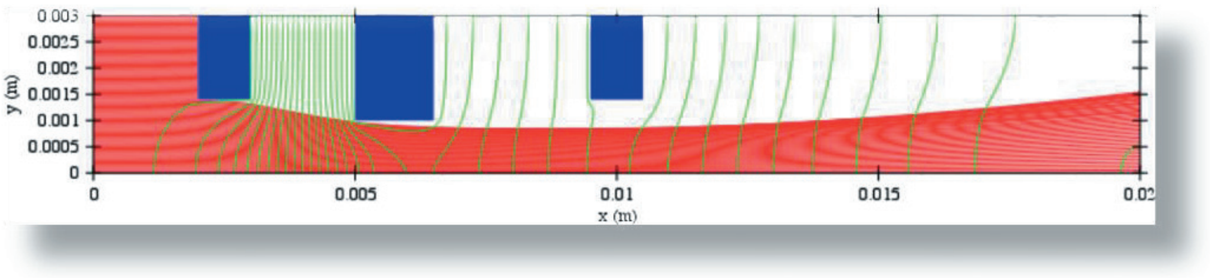

Figure 1: Schematics indicating ion extraction through a grid aperture.

The accelerator grid is biased to a large negative potential, typically between -100V and -500V with respect to ground (or common potential). Ions that diffuse from the bulk plasma within the discharge chamber to the plasma (sheath) edge upstream of the screen grid are accelerated across the plasma sheath and either impinge on the upstream face of the screen grid or pass through the apertures, where they are then accelerated to high velocity due to the high potential difference between the screen and accelerator grid. The beam divergence is a function of the geometrical parameters of the "Ion Optics System" like the grid thicknesses and the distances between the grids and also on voltages and the plasma parameters. An intelligent design of the ion optics system ensures the good performance of the thruster and determines the beam divergence [Maria]

D. Thrust and Isp

As stated previously, the thrust generated is equivalent to the net force acting on the grids due to the extraction and acceleration of the ions. Thrust is proportional to the rate of change of momentum of the expelled propellant, dependent on ion beam current, ion mass and velocity of the ions (ion velocity being proportional to the square root of the beam voltage). Thrust can be approximated by:

$$F = \eta_d \cdot I_{beam} \cdot \sqrt{2\frac{m_i}{q_i}\left(U_+ + V_P\right)} = 50.87\mu N \cdot \frac{I_{beam}}{mA} \cdot \sqrt{\frac{U_+ + V_P}{kV}} \qquad \textbf{Eq. 2}$$

where η_d is a thrust correction factor due to beam divergence, m_i is the mean ion mass, which for xenon is m_i= 131.3 AMU, q_i is the mean ion charge q_i= 1.01e (assuming <1% ratio of singly-to-doubly charged ions), U_+ is the positive high potential applied to the screen grid and V_p is the plasma potential, which can be assumed to be approx. 20-25V.

$$I_{sp} = \frac{\eta_m}{g_o} \cdot \sqrt{2\frac{q_i}{m_i}\left(U_+ + V_P\right)} = 3927.6s \cdot \eta_m \cdot \sqrt{\frac{U_+ + V_P}{kV}} \qquad \textbf{Eq. 3}$$

E. Thruster Power

The power of the thruster is a summation of the ionisation power, which is necessary to produce and extract enough current and the extraction/acceleration power, that accelerate the ion current to the necessary kinetic energy. The electric power necessary for the ionisation comes in the form of radio frequency EM field from the Radio Frequency Generator and its amount is a function of ion current and the size of the thruster. A calculation of the RF power needs a large amount of the EM simulation of the thruster. The necessary electric filed power for acceleration of the ions will be delivered by the Positive High Voltage power Supply. The amount of the DC power of the PHV can be easily calculated as the multiplication of the current and the voltage of the PHV. The negative High Voltage has only a minor role in the calculation of the total power, as its current and voltage is only 1-2 % of the PHV current and voltage.

$$P_{RFG} \propto f(I_{beam}, D)$$
$$P_{Beam} = I_{Beam} \times V_{PHV} \quad \textbf{Eq. 4}$$

Where ***D*** is the diameter of the thruster.

As the beam power is directly proportional to the V_{PHV} and the thrust is proportional to $V_{PHV}^{1/2}$, by choosing a higher V_{PHV} we would need higher power to achieve the same thrust. From the other side, as the velocity of the ions are proportional to $V_{PHV}^{1/2}$, the higher acceleration voltage would lead to higher ***Isp*** of the thruster. For a real trade-off also the beam divergence plays a decisive role. The higher V_{PHV} would lead generally to lower beam divergence and therefore higher thrust transferred to the target.

F. Effect of the thruster sizing in the thruster performance

The size of the thruster or its diameter determines the maximum current, which can be extracted from the thruster. A larger diameter means higher achievable thrust. However, this larger size will require higher discharge power.

IV. RESULTS OF THE MODELLING

Figures 3 and 4 show the results of the modelling of the thruster. Figure 3 shows the power consumption of the two thrusters as a function of the transferred impulse to the target and for different beam voltages. In the model for each beam voltage, an optimized ion optics is calculated and the size of the thruster is derived from the necessary thrust. The near field beam divergence and the neutralizer electron effect[8] give the amount of the transferred impulse on the target. The Isp, given in figure 4 is calculated from the thrust and the gas flow in each thruster.

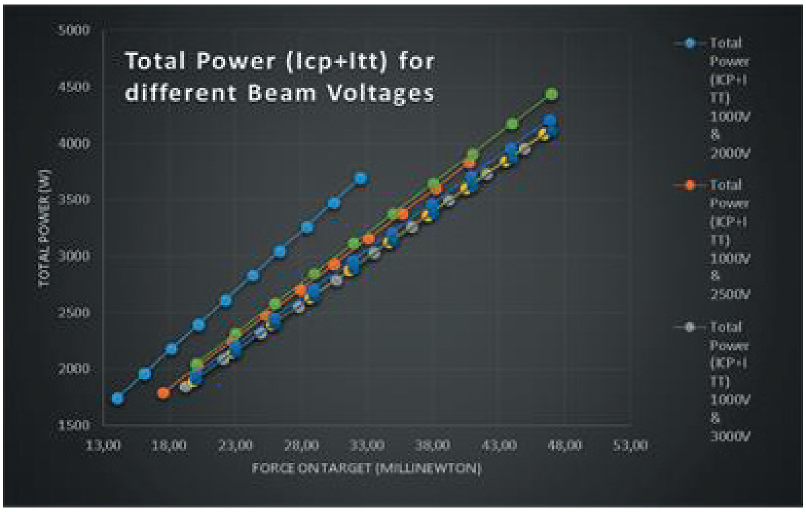

Figure 3. The total power consumption of the propulsion system (ITT and ICT) as a function of transferred thrust to the target for different beam voltages

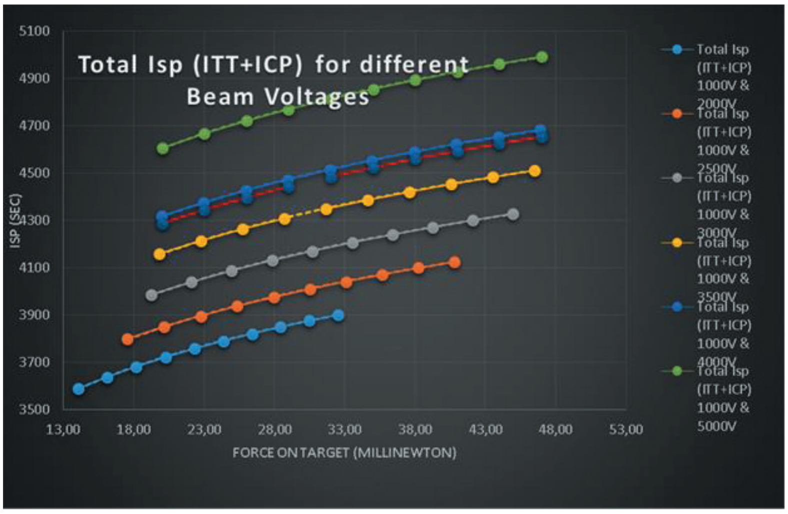

Figure 4. The total power consumption of the propulsion system (ITT and ICT) as a function of transferred thrust to the target for different beam voltages

A. Effect of positive high voltage (beam energy) in the thruster performance

The beam divergence is a function of the beam voltage. A higher beam voltage will result in a lower near field if accompanied by a proper ion optics. However, the most important effect of the higher beam voltage is the reduction of beam divergence in far field (7m and higher). However, the higher beam voltage would lead to higher power consumption for a specific thrust or higher power to thrust ratio.

That means if we choose the beam voltage too low, we will not be able to transfer a large part of the initial thrust to the debris and we will lose much of the thrust that we can produce for a specific amount of power. From the other side choosing a too high voltage will also reduce the value of producible thrust for a specific power.

The figure 5 shows the variation of the thrust to power ratio at a distance of 7m as a function of the beam voltage. The thrust here is defined as the force, transferred to the target. We see that the optimum beam voltage would be between about 3500Volts.

It is to mention that the power calculated here is the sum of the power needed for the ITT and ICT thrusters. In these calculations we also have to take into account the beam voltage of the ICP.

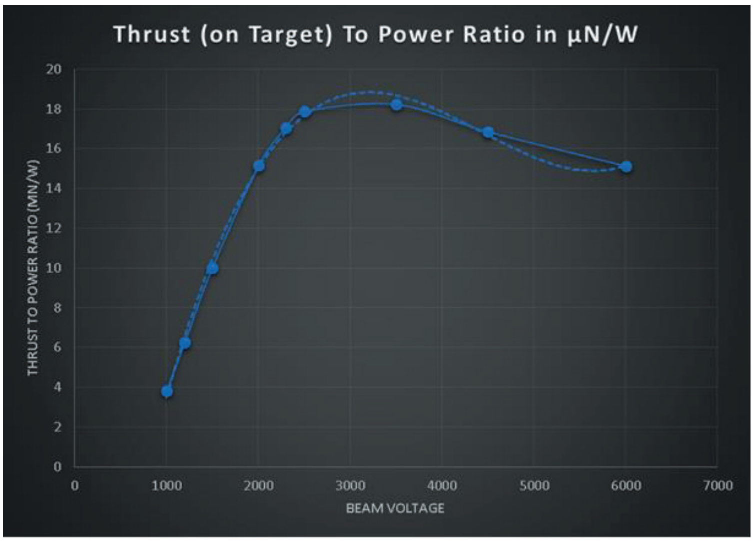

Figure 5. the ratio of transferred thrust to Power ratio as a function of the beam voltage

V. Thruster Design

A. Ionizer Design

The amount of the current, which can be extracted from a thruster is a direct function of the plasma density in the thruster and the electron temperature in it. The current then determines the produced or transferred thrust. Therefore for a valid prediction of the thrust, a precise calculation of the plasma properties in the thruster is needed. The plasma parameters are however a function of the gas pressure in the chamber and the electromagnetic discharge in it. For better understanding of the behavior of the thruster, electromagnetic modelling was performed. The model gives the electromagnetic field in the different regions of the discharge chamber of the thruster. These values can be then used to calculate the plasma parameters in the different regions of the thruster. Also the loss of RF power in different parts of the thruster outside the discharge chamber (RF losses) could be simulated. These information help for a optimisation of the thruster parts specially the thruster discharge chamber. A detailed discussion about the modelling of Radio Frequency Ion Thrusters is given in [11]

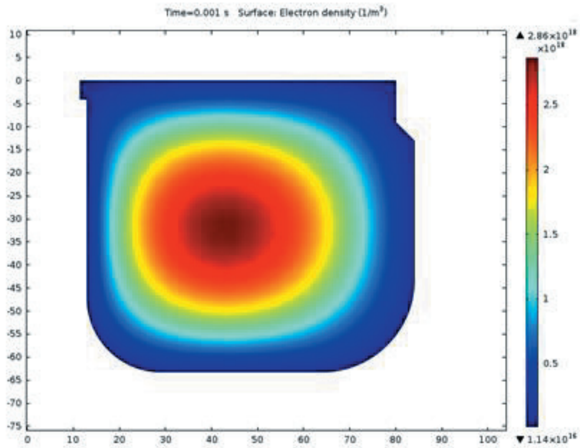

Figure 6: Plasma density distribution inside the thruster.

B. RF Circuitry

The whole RF circuitry is composed of an RF generator, coaxial cable and the thruster with reflected impedances of the coil, structure and plasma. Figure 7 shows an equal circuit for the thruster-RFG system. The main currents are indicated as well for better understanding. Note that all calculations were made assuming that the thruster operates at its operational point.

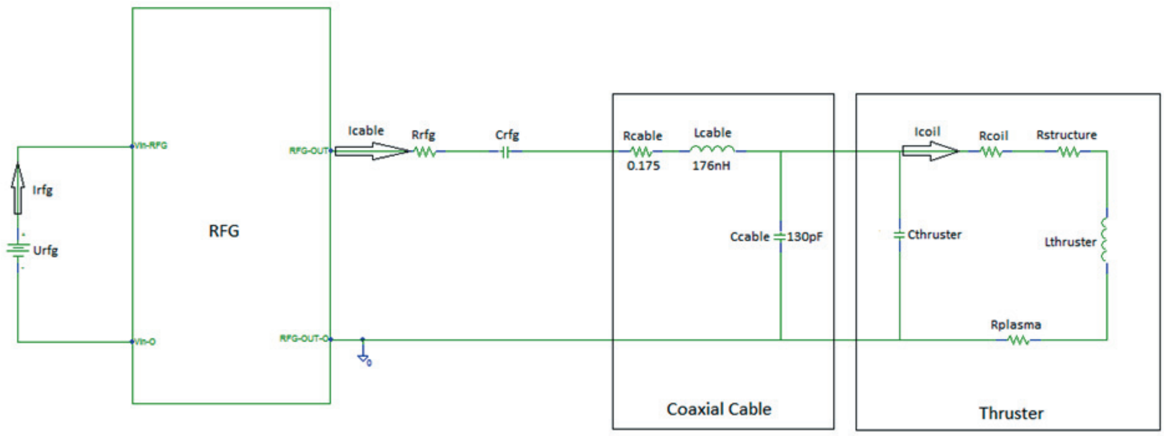

Figure 7: RF circuitry schematics including coaxial cable and thruster.

C. Power loss Analysis

Table 1 details the complete power loss analysis of the thruster. As the table indicates, negligible inductive (or coupling) power losses occur in accelerator grid, decelerator grid and cathode. This is mainly because the magnetic fields are shielded by the screen grids, in case of accelerator and decelerator grids, and by the plasma which acts as a conductor in case of the cathode. Furthermore, a substantial amount of power is lost in the coaxial cable and the RF generator itself. To reduce this power, the cable length and the number of electrical connections has to be reduced as much as possible. Reducing coil current would also help, but one has to remember that coil current range is also limited by RF generator's maximum voltage drop. Finally, the power loss to the screen grid is strongly influenced by the grid material. In this study it was assumed that grids are made from titanium. Changing to a material with higher conductivity, molybdenum, for instance, would decrease the inductive losses. However, there are other challenges associated with sputtering and thermal expansion of the grids that will be discussed in next chapter.

Table 1: Power loss distribution for the current thruster design at A operational point.

RF generator input power (P_{rfgin})	232W
Power lost due to RF generator's internal resistance (P_{Rrfg})	10.4W
Power lost due to coaxial cable's resistance (P_{Rcable})	9W
Power lost due to coil's internal resistance (P_{Rcoil})	6.2W
Power lost due to coupling between the coil and plasma ($P_{Rplasma}$)	204W
Power lost due to coupling between the coil and screen grid (P_{Rscrn})	1.86W
Power lost due to coupling between the coil and accel grid (P_{Raccel})	$\approx 0W$
Power lost due to coupling between the coil and deccel grid ($P_{Rdeccel}$)	$\approx 0W$
Power lost due to coupling between the coil and case (P_{Rcase})	0.53W
Power lost due to coupling between the coil and cathode (P_{Rcat})	$\approx 0W$

The following table gives the approximate plasma parameters that should be present during the operation at the beam current of 0.4A and gas flow rate of 6.56sccm. This operational condition was deemed to be the most optimum for the mission design based on beam divergence profile.

Table 2: Plasma parameters in the thruster at A operational point

Neutral gas pressure (mTorr)	0.223
Neutral gas density (1/m^3)	5E18
Ion density (1/m^3)	2.8E17
Beam current density (mA/mm^2)	66
Plasma potential (V)	28.7
Plasma skin depth (mm)	16
Electron neutral collision frequency (Hz)	1.2E6
Electron ion collision frequency (Hz)	7.6E5
Stochastic collision frequency (Hz)	9.8E6
Effective collision frequency (Hz)	1.18E7
Electron temperature (eV)	5.6

D. Grid design

One of the major challenges when designing an ion thruster is the design of the ion acceleration grids. The Grid Assembly consists of a three grid extraction system (screen, accelerator and decelerator grids), and spacers and

holders made of different materials, shape and thickness. The Grid Assembly has been designed in order to minimize misalignments due to thermal distortions. An optimal geometry was selected for the design of the grid assembly, with a number of apertures equals to 982.
The challenges associated with thermal expansion of the grids and grid alignment will be analyzed. Due to low thermal expansion coefficients, low sputtering yield and high strength, two materials were chosen as the best candidates; these are Titanium and Carbon-Carbon composite (C-C).

VI. Conclusion

A thruster is designed according to the requirements of the LEOSWEEP project. The main restrictions are the power dedicated to propulsion subsystem and the requirement for a low beam divergent, which will ensure a maximum impulse transfer to the target. A model is developed, that predicts the performance of such specialized thruster. Using the model the design parameters of the thruster like the size of the thruster, the ion optics geometry and the beam voltage is determined. A thruster with these design parameters is modeled and constructed. The thruster is now under manufacturing.

Acknowledgments

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