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ION BEAM SHEPHERD MISSION LEOSWEEP: MISSION DESIGN TO ION BEAM THRUSTER TESTING

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ABSTRACT:

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.

The IBS demostration mission requirements which have been clearly formulated and will establish the operational frame for the LEOSWEEP project develoment are presented in this paper. These requirements include IBS mission objective, platform technologies, plume expansion software and impulse transfer thrusters specification.

This paper describes the design of the LEOSWEEP mission, spacecraft for such a mission and development model thruster which is manufactured and tested against major spacecraft design and mission requirements obtained in the course of project.

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.

The first results of the tests will be presented. Also, a genuine method to decrease the beam divergence will be described, which is implied in the thruster design.

ABBREVIATIONS AND ACRONYMS:

ADR	Active Debris Removal
IBS	Ion Beam Shepherd
DM	Development Model
ITT	Impulse Transfer Thruster
ICT	Impulse Compensation Thruster
EP	Electric Propulsion
CP	Chemical Propulsion
GNC	Guidance, Navigation and Control
PPU	Power processing Unit
DoF	Degree of Freedom

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RIT	Radio Frequency Ion Thruster (inductively coupled)
GIE	Gridded Ion Engine
RF	Radio Frequency
IOS	Ion Optic System

1. INTRODUCTION

One key technological challenge of active debris removal (ADR) is the implementation of an efficient and reliable removal concept that is versatile enough to be applicable to different types of debris in subsequent missions with minimum design modifications. This fact motivates the demonstration of contactless ion beam shepherding [1] as a key milestone before large scale removal missions can be implemented in the future.

2. IBS AND LEOSWEEP MISSION

The LEOSWEEP mission is aimed at demonstrating contactless removal of a large (ton-class) debris object in low earth orbit by using the beam momentum of an ion engine. The beam is kept pointed at the target debris from an ion beam shepherd spacecraft (Fig. 1) (IBS) coorbiting at a few meters distance (nominally 6-8 meters) and carrying two main electric propulsion units: an impulse transfer thruster (ITT) acting on the debris and an impulse compensation thruster (ICT) balancing the net force on the shepherd spacecraft. This solution avoids the complexity and risk of close-proximity control and mechanical contact with a non-cooperative target with unstable attitude motion (tumbling or spinning) and can be applied to targets of generic shape with minimum impact on mission design. Multiple removal operations are possible and could even be considered in the last phase of a demo mission if enough leftover propellant is available.

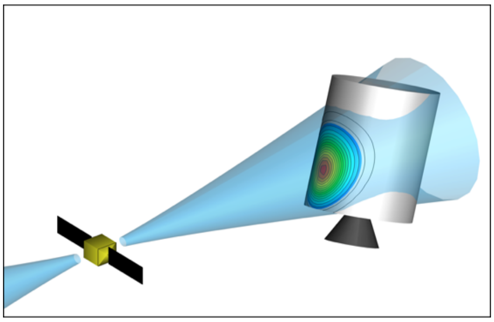

Figure 1. Schematic of the ion beam shepherd (IBS) concept

3. SPACECRAFT DESIGN AND PROPULSION SYSTEM REQUIREMENTS

The IBS is essentially a “contactless” actuator, which allows modifying the orbit and/or the attitude of a generic object (the “target”) using the momentum transferred from one or more ion beams produced by Electric Propulsion (EP) thrusters onboard a nearby spacecraft (the “shepherd”), and properly pointed towards the target by means of the shepherd’s 3-axes position and attitude control that includes Chemical Propulsion (CP) thrusters.

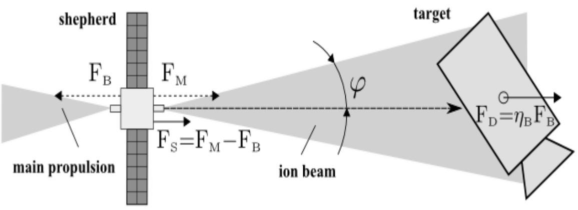

Figure 2. Schematic of the IBS concept

In order to produce a continuous contactless actuation on the target, the shepherd satellite main propulsion system must employ at least two similar thrusters: an Impulse Transfer Thruster (ITT) pointed at the target and an Impulse Compensation Thruster (ICT) generating a counteractive force on the shepherd in order to avoid the latter from accelerating away (Fig. 2). A small beam divergence allows the shepherd to operate efficiently (i.e. with almost full beam overlap and momentum transmission) at a safe distance from a target body, specified to between 7 and 8 meters for the LEOSWEEP application case. This imposes stringent requirements both at Propulsion and Guidance, Navigation and Control (GNC) subsystems, specifically (amongst others):

- The GNC system shall be able to control, at any time during the shepherding phase, the IBS relative position and velocity with the following accuracy:
    - Maximum allowed relative position error (in all directions): 60cm (3-sigma).
    - Maximum allowed relative velocity error (in all directions): 1.5cm/s (3-sigma).
- The ITT shall produce enough thrust to inflict a 30mN effective force on the target.
- Both thrusters (operating at the same time and including their PPUs) shall consume less than 3.3kW.
- Thrusters shall weight less than 3.5kg (both together).

- The RCS shall provide the spacecraft with 6 Degrees of Freedom (DoF) movement capability, for both angular momentum management and different manoeuvring purposes.

The Shepherd subsystems and platform have been designed taking into account these and other specific design challenges. As a result of a first complete design iteration, a 545kg platform has been drafted, providing up to 4.4kW of average power during the whole mission duration, thanks to two 11m^2 solar arrays and associated batteries. This power is mostly used by the EP system during the orbit raising and shepherding phases. It is important to notice that, during eclipse periods, both ITT and ICT are turned off for power and mass savings.

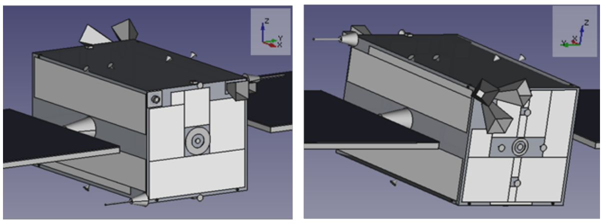

Figure 3. Shepherd spacecraft preliminary configuration

4. BEAM TRANSPORT

The expansion of the plasma plume of the ITT into vacuum and its impingement onto a target space debris to transmit the deorbiting force is a crucial aspect of the project. Understanding the phenomena that give rise to plume divergence (which limits the momentum transfer efficiency) over distances of about 10 m allows to optimise the thruster design and the mission geometry.

Within the LEOSWEEP project, the EP2 group at UC3M is in charge of studying the plasma plume expansion problem. To this end, two major developments have been undertaken: first, a set of fluid plume models and codes termed EASYPLUME were derived and implemented to enable the fast estimation of the plasma properties at the space debris object position. With this code it is possible to compute a reasonably good approximation of the transmitted force and torque. More information about EASYPLUME can be found on [2].

Second, an advanced hybrid PIC/fluid code named EP2PLUS capable of simulating the 3D plasma plume expansion is being developed and the first version almost concluded. This code allows to recover the ion energy distribution function and account for collisional effects (e.g. charge-exchange collisions), asymmetries that may exist in the plume (e.g. by an external neutralizer mounted on the side of the thruster), and study complex 3D configurations of the IBS satellite plus the debris object. Plasma and neutral backflow to the IBS can be computed. Intelligent particle population renormalization algorithms and an expanding grid approach can be used to deal with the decreasing number of particles per cell in the expansion. The EP2PLUS code is also a flexible computational platform that can easily be extended with new modules. In the future, the influence of an external uniform magnetic field on the electron population and therefore on the plasma plume expansion will be included.

For reference, an example of a plume simulation with a target debris at an asymmetric position with respect to the plume centerline is finally shown in Fig. 4. More information can be found in the companion paper in this conference [3].

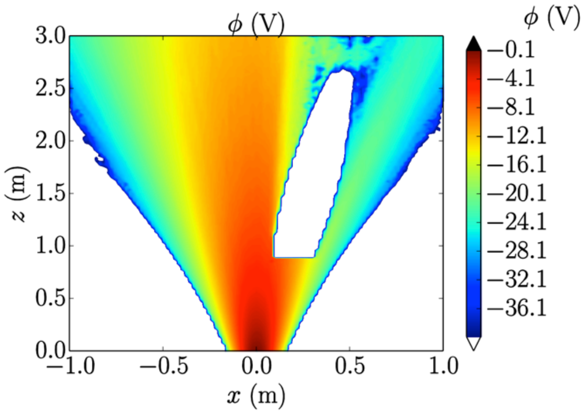

Figure 4. Plasma potential response in an EP2PLUS simulation of an expanding plasma plume with an offset cubic obstacle embedded in it

5. PROPULSION SYSTEM

With respect to both, the requirements to the propulsion unit given as an outcome of the complex mission analysis shortly mentioned in section 3 of the current paper, and the general consideration on the momentum transfer efficiency in the longitudinal direction arising from the modeling of beam transport as described in section 4, more detailed requirements to the propulsion system were formulated and listed hereafter:

- Total power: 3.3 kW for both thrusters on bus level, giving about 2.8 kW for both on propulsion system level given efficiency of 85%.

- Thrust on target: not less than 30 mN gives 31 mN required on thruster output.
- Divergence: not more than 10 degree in 10 m giving under 7 degree required divergence in the near field.
- Thruster weight: less than 3.5 kg for both thrusters.
- Ion energy in the beam should be as high as possible and electron temperature should be as low as possible for both, reaching lower divergence and effectively transporting the beam in long distance.

Given such strict requirements for the divergence angle very few Electric Propulsion types could be considered for the LEOSWEEP mission. TransMIT proposed the Radio Frequency Ion Thruster (RIT) concept to be used. Such thrusters use an electrodeless inductive discharge for the generation of plasma and their design is based on the standard configuration of an inductively coupled plasma source. The thrust generated by a 'gridded' ion engine (GIE) is a result of the net force acting on grid electrodes used to extract ions from a plasma and then accelerate them out of the thruster.

Based on the initial requirements, a first modeling of the basic parameters, such as, size and operational voltage was performed in order to match into the given power. The detailed optimization process was presented during the IEPC 2015 [4]. In the following table, the final performances of the modeled ITT are shown:

Table 1. Modelled ITT performances

	Parameter value
Thruster Diameter (Extraction System)	17 cm
Thrust on target	28-35 mN
Specific Impulse	5300 s
Thruster power (@31 mN)	<1400 W
Beam voltage (@31 mN)	3500 V
Beam current (@31 mN)	315 mA
Beam divergence (near field)	5-7 °
Mass flow	0.6 mg/s

An optimisation for the ICT was also performed thus that requirement for the total power could be met. In the Table 2 the summarised performances of the ICT are shown:

Table 2. Modelled ICT performances

	Parameter value
Thruster Diameter (Extraction System)	14 cm
Thrust on target	35-45 mN
Specific Impulse	3800 s
Thruster power (@40 mN)	<1200 W
Beam voltage (@40 mN)	1200 V
Beam current (@40 mN)	750 mA
Beam divergence (near field)	26-28 °
Mass flow	1.2 mg/s

Since one of the most important factors for the beam transport turned out to be a low electron energy, it has been proposed that the neutraliser for the particular ITT design will be placed into the middle of the thruster in order to minimise the coupling energy and thus the total energy of the electrons.

In order to satisfy the requirement for the divergence, the Grid System has been simulated to define the geometry of the single apperture which meets the conditions for the available voltage and necessary ion current. Plasma parameters which were the input for this simulation were identified using the Comprehensive Radio Frequency Ion Thruster Electromagnetic Model described in the paper [5].

6. THRUSTER DESIGN

Based on the modelling, a preliminary thruster design was carried out. The thruster comprises the Ionizer (Discharge Chamber together with RF-coil and its attachment); Grid System, or in other words, the Ion Optic System (IOS - set of the electrodes for the electrostatic acceleration of the ions to form the beam); high voltage and gas feeding contacts and the supporting structure. Herefater, we will discuss further the particular challenges and the designs features of the specific sub-assemblies.

6.1 Ionizer sub-assembly design

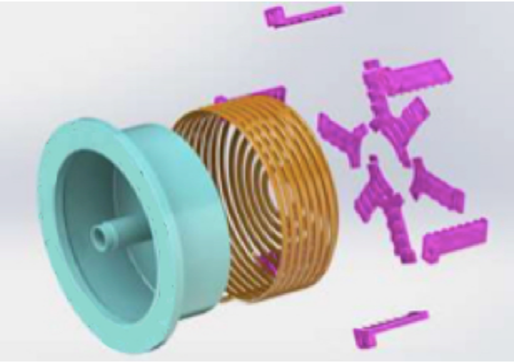

Figure 5. Ionizer sub-assembly of the ITT: Discharge Chamber, Coil and Coil holders are depicted

One of the main functional parts of the RIT thruster is the Ionizer where plasma is being produced in an inductively coupled RF discharge with neutral gas injected inside the Discharge Chamber and power induced from the RF-generator through the coil bounding the ceramic vessel. In order to satisfy the structural stability, disturbed by the vibrations and thermal loads, holders of a specific design are used.

TransMIT proposed a more complex geometry for the ITT thruster than the one normally used in conventional RITs or any other Gridded Ion Thruster which are usually having a discharge chamber of cylindrical shape. With respect to the proposed position of the neutraliser in the middle of the thruster beam, the Discharge Chamber became a coaxial toroid as can be seen in Figure 5. Middle cylinder has flange for the Neutraliser attachment.

Once full-sized design has been prepared, a comprehensive plasma modelling was performed to optimise the final geometry of the Discharge Chamber and the Coil to minimise RF-power and smooth the plasma properties in the near grid area. As a result, the final design was set up.

6.2 Ion Optic System sub-assembly design

The Ion Optic System in an GIE is the responsible unit for the extraction and acceleration of the ions from the Discharge plasma and beam forming. All the important thruster parameters, like Thrust, Specific Impulse, divergence and Life time are in high interdependence with the operational condition and design parameters of the IOS.

The Grid System usually comprises from two or three thin parallel plates with multiple coaxial apertures. Plasma parameters inside of the Discharge Chamber together with working voltage identified in the previous steps (see section 5) determine, with the help of the modelling in specialised softwares, the particular geometry of the grids (thickness, hole sizing and distance between the grids).

Once single apperture geometry was optimised, macroscopic design was suggested (Figure 6). Any IOS is very complex due to the fact that high thermal load influences each Grid changing its macroscopic geometry, however distance between Grids and apertures coaxiality should stay constant throughout the Thruster operation in order to let Thruster performances constant. Iterative thermal modelling has been performed in the frame of the LEOSWEEP project to identify the best set of materials and form of the IOS parts to be used. Main conclusions of this construction step were the following:

- Flat geometry is preferable over curved for the LEOSWEEP project;
- Carbon-carbon material is chosen between other candidates;
- Thermal modelling demonstrated that floating seal of the grid edges is the best compromise for work in predicted operational condition.

As well as, in the case of the Ionizer, the macroscopic Grid System design became even more complex due to the central position of the Neutraliser and thus, a hole in the middle of every Grid apeared (Figure 6).

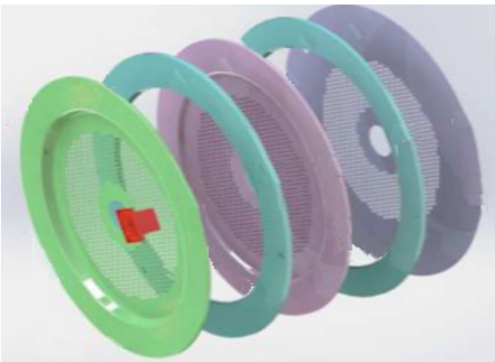

Figure 6. Ion Optic System sub-assembly of ITT: screen, accel and decal grids and spacers (marked in light blue)

6.3 Final ITT Design

After the Ionizer and the Grid System were defined, the design of the supporting structure for the integration of all the sub-assemblies, as well as, the design for the High Voltage and Gas Feeding lines were proposed. Figure 7 shows the finalised assembly of the ITT developed under the LEOSWEEP project.

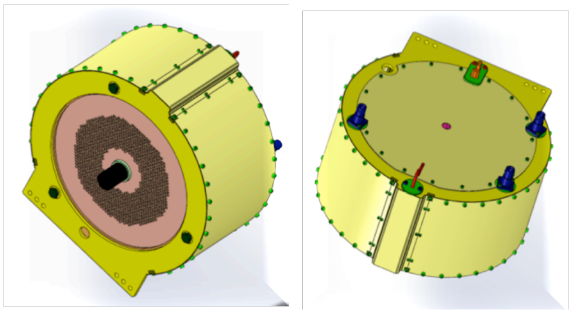

Figure 7. ITT assembly

Total size of ITT prototype is 26cm*22cm*17cm (including the Neutraliser installed). Mass of the thruster is under 5300 g. Size and mass of the prototype can be reduced on later development stages. ITT prototype parts have been produced and first integration took place at the end of October 2015.

7. TEST ACTIVITY

A laboratory test campaign is considered as a crucial objective for the LEOSWEEP project as its results will allow validating previously obtained analytical and numerical results pertaining to different aspects of the ion-beam physics and beam-target interaction. Test activities took place from October 2015 to March 2016 and comprised such topics as:

- Experimental confirmation of the ITT work;
- Experimental investigation of the beam transport to the long distances;
- Transmited force measurements;
- Secondary effects, like sputering of the trarget by the ion beam, and other interaction between the beam and the target spacecraft material.

All the tests have been conducted in environments as close as possible to the ones an IBS will face in a real mission.

First tests on the Impulse Transfer Thruster were performed at the Southampton University Electric Propulsion Laboratory Test Facility in a clean vacuum environment.

An ITT Thruster Characterisation aiming at verifying the predicted operation of the thruster and determining performance and operational range of the developed ion thruster w.r.t the system requirement specification for LEOSWEEP was performed.

The characterisation included a functional test and all thruster voltages, currents, powers, and mass flow rates were measured to characterise the thruster operating point. Thrust was calculated to high accuracy as for any RIT.

Ion beam diagnosis in the near and far field, as well as, impulse transfer measurements have been recently completed at the DLR STG-ET facility. Data from these tests is currently being analysed.

An extensive test program was performed in the Institute of Technical Mchanics of the National Academy of Sciences of Ukraine on the irradiation of the surface samples of the target candidates by an ion beam equivalent to the ITT one. Results of those tests are now being under analysis too.

8. TEST RESULTS

Initial functional tests of the ITT demonstrated feasability of all the sub-systems of the thruster. On full power operation during March 2016 at DLR premises, the following parameters were obtained:

- Thrust ≈ 28 mN;
- RF Power: 275 W;
- Mass Flow: 0.57 mg/s;
- Beam current: 290 mA;
- Drain current: < 2 %;
- Divergence (preliminary evaluation): < 7°;
- Total power is under 1300 W.

Figure 8 demonstrates ITT in operation on a full power.

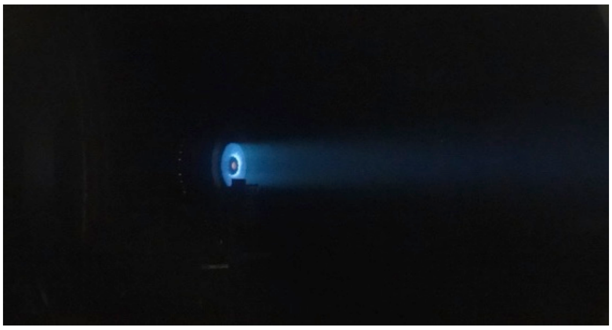

Figure 8. ITT at DLR facility

9. SPECIAL CONSIDERATIONS AND CONCLUSION

A 17 cm Radio Frequency Ion Thruster design has been developed in order to satisfy the requirements obtained in the frame of detailed examination of the LEOSWEEP mission and Spacecraft specifications. The strict requirements for the divergence are feasible and have been demostrated with the preliminary test results.

A detailed results assessment will be carried out to quantify the LEOSWEEP concept performance, and provide feedback on the proposed design options.

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