

# Design, manufacturing and characterisation of the Impulse Transfer Thruster for an Ion Beam Shepherd Mission: results of 3-years FP7 project LEOSWEEP

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Maria Smirnova<sup>1</sup> and Aloha Mingo Perez<sup>2</sup>  
*TransMIT GmbH, Giessen, 35394, Germany*

D. Feili<sup>3</sup>  
*European Space Agency, Keplerlaan 1, Noordwijk ZH, 2201 AZ, The Netherlands*

Mantas Dobkevicius<sup>4</sup>  
*University of Southampton, Southampton, SO17 1BJ, UK*

*and*

Horst W. Loeb<sup>5</sup>  
*University of Giessen, Giessen, 35392, Germany*

**Abstract:** The 3-years Seventh Framework Programme (FP7) LEOSWEEP project, devoted to the development of the ion beam shepherd (IBS) technology for the removal of large debris object from crowded regions in low earth orbit (LEO), raised various questions related to mission scenarios, associated techniques and legal frame developing. This paper outlines works designated to the design, manufacturing and first characterisation of the one of the crucial to IBS realisation technology: thruster that is able to satisfy major LEOSWEEP requirements.

## Nomenclature

<i>FP7</i>	=	Seventh Framework Programme (European Union's Research and Innovation funding programme for 2007-2013)
<i>LEOSWEEP</i>	=	Improving Low Earth Orbit Security With Enhanced Electric Propulsion
<i>IBS</i>	=	Ion Beam Shepherd
<i>LEO</i>	=	Low Earth Orbit
<i>ITT</i>	=	Impulse Transfer Thruster
<i>ICT</i>	=	Impulse Compensation Thruster
<i>DM</i>	=	Development Model
<i>RIT</i>	=	Radio Frequency Ion Thruster
<i>GIE</i>	=	Gridded Ion Engine

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<sup>1</sup> Director of Project Division, Project Division for Ion Sources for Material Processing, maria.smirnova@transmit.de.

<sup>2</sup> Electric Propulsion Engineer, Project Division for Ion Sources for Material Processing, aloha.mingo@transmit.de.

<sup>3</sup> Electric Propulsion Engineer, TEC-MP, davar.feili@esa.int.

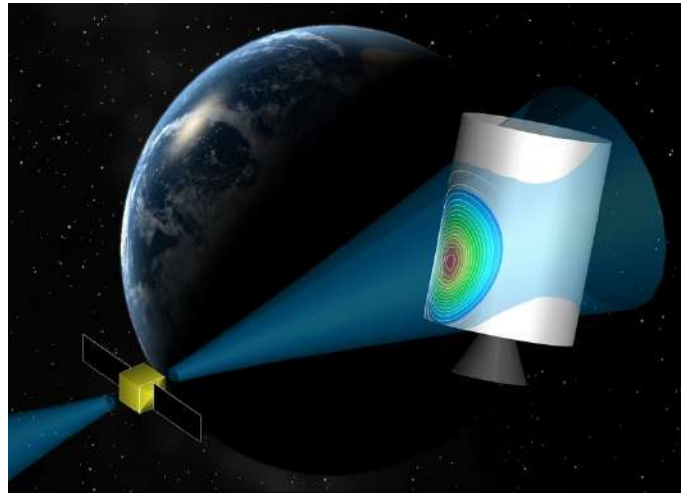
<sup>4</sup> PhD candidate, Astronautic Research Group, mantasdb@gmail.com.

<sup>5</sup> Emeritus Professor.

RF = Radio Frequency  
IOS = Ion Optic System

## I. Introduction

**L**EOSWEEP stands for Improving Low Earth Orbit Security With Enhanced Electric Propulsion and assumes concept of “contactless” Space Debris (“target”) removal by the mean of momentum transfer through the ion beam produced by electric propulsion on board of a nearby spacecraft (“shepherd”). This concept was proposed in 2010 by the Space Dynamics Group research team from the Polytechnic University of Madrid and named Ion Beam Shepherd Concept (IBS)<sup>1</sup>. Schematic of the IBS concept is depicted on Figure 1. In order to allow relative position of the target and the shepherd stay constant at least two opposite directed thrusters should be installed:



**Figure 1: Schematic of the IBS.**

- Impulse Transfer Thruster (ITT) pointed at the target with a low divergence to allow efficient use of the momentum generated;
- Impulse Compensation Thruster (ICT) to compensate ITT momentum on the shepherd spacecraft as well as to avoid the target from accelerating away.

This paper will summarize TransMIT team activities under LEOSWEEP project on design, manufacturing and testing of a Development Model (DM) of the Impulse Transfer Thruster performed against major LEOSWEEP requirements.

## II. Impulse Transfer Thruster

### A. Main propulsion system requirement for the LEOSWEEP spacecraft

In line with the requirements to the propulsion unit given as an outcome of the complex mission analysis and the general consideration on the momentum transfer efficiency in the longitudinal direction arising from the modelling of beam transport (both precisely investigated in the frame of the LEOSWEEP project), detailed requirements to the propulsion system were formulated that are listed hereafter:

#### - Total power

Total power of 3.3 kW for both ITT and ICT thrusters were allocated on bus level of a 545kg spacecraft as a result of comprehensive platform design study. Taking into account efficiency of about 85% this gives total of 2.8 kW power for two thrusters on propulsion system level.

#### - Thrust on target

Minimum thrust of 30 mN on target was calculated to be sufficient for demonstrator mission manoeuvres. This value results in 31 mN thrust requirement on ITT output.

#### - Divergence

Conservative number of 10 degrees divergence in 10 m distance (between the shepherd spacecraft and the target debris) was set. This value recalculates into required divergence of about 7 degrees on the ITT output taking into account beam transport studies<sup>2,3</sup>.

#### - Thruster weight

Strict requirement was given for total weight of Propulsion system to be less than 3.5 kg for both thrusters.

#### - Ion energy in the beam

In order to productively transfer generated thrust from the thruster to a distance of about 10m it is necessary to introduce as high as allowed by available power ion energy whereas electron temperature should tend to minimum possible value.

### B. Thruster optimization

Those severe requirements wouldn't enable original project idea of the available thruster modification to be implied. Instead completely new thruster design should have been proposed, realised and tested in about 2 years'

timeframe available. Very few Electric Propulsion types could be considered for the LEOSWEEP mission mainly due to their divergence characteristics. 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 modelling of the basic parameters, such as, size and operational voltage was performed in order to match into the given power. Consideration was given to the following factors, weighted with reference to the importance to development model (DM) thruster development in the frame of LEOSWEEP contract.

- Thruster Performance: the expected contribution of the design option to improved thruster performance (eg. reduced thruster power, higher propellant utilization 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 in terms of their influence to the thruster performances are thruster size and beam voltage. The thruster size determines the maximum thrust of the thruster and affect the discharge power consumption and the mass efficiency of the thruster. The task of ITT design on the very first modelling and optimization stage was expanded towards optimization of the full Main Propulsion system including ICT optimization in order to satisfy mass and power available onboard.

The detailed optimization process was presented during the IEPC 2015<sup>4</sup>. In the following table, the final performances of the modelled 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

A number of design improvements were evaluated and implemented into the design of the DM ITT. So, 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. It is speculated that the total energy of the electrons will be minimised in this way satisfying one of the most important factors for the effective beam transport - low electron energy.

In order to be in line with the requirement for the divergence, the Grid System has been simulated to define the geometry of the single aperture which meets the conditions for the available voltage and necessary ion current gathered through the thruster optimisation process. Plasma parameters which were the input for this simulation were identified using the Comprehensive Radio Frequency Ion Thruster Electromagnetic Model described in the Ref. 5.

### C. Thruster design

Based on the modelling results, a preliminary thruster design was carried out. The thruster consists from the following sub-assemblies:

- the Ionizer (Discharge Chamber together with RF-coil and its attachment);
- the Ion Optic System (IOS - set of the electrodes for the electrostatic acceleration of the ions to form the beam);
- high voltage contacts;
- gas feeding line;
- the supporting structure.

Particular challenges and the design features of the specific sub-assemblies will be described further.

#### Ionizer sub-assembly design

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.

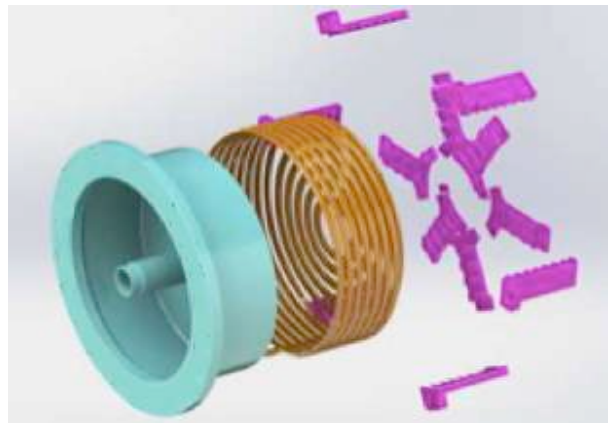
TransMIT proposed a more complex geometry for the ITT thruster than the one normally used in conventional RITs or any other Gridded Ion Thruster which are usually having a discharge chamber of cylindrical shape. With respect to the proposed position of the neutraliser in the middle of the thruster beam, the Discharge Chamber became a coaxial toroid as can be seen in Figure 2. 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.

#### 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 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 determine, with the help of the modelling in specialised software's, the particular geometry of the grids (thickness, hole sizing and distance between the grids).



**Figure 2: Ionizer sub-assembly of the ITT: Discharge Chamber, Coil and Coil holders are depicted**

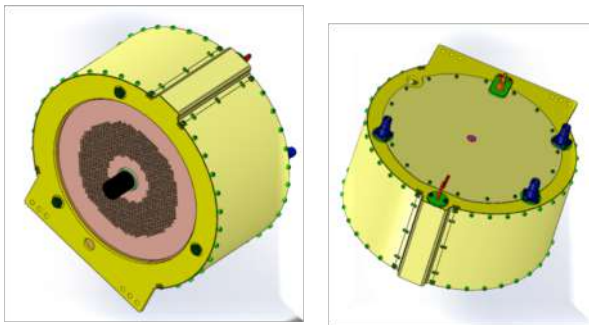


**Figure 3: Ion Optic System sub-assembly of ITT: screen, accel and decal grids and spacers**

Once single aperture geometry was optimised, macroscopic design was suggested (Figure ). 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 coaxially 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 appeared.



**Figure 4: ITT assembly**

#### 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 4 shows the finalised assembly of the ITT developed under the LEOSWEEP project.

Total size of ITT prototype is 26cm\*22cm\*17cm (including the Neutraliser installed). Mass of the thruster prototype 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 Figure 5.



**Figure 5: DM ITT integrated**

#### **D. Test Activities**

A laboratory test campaign was considered as a crucial objective for the LEOSWEEP project as its results would 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 on designed performances;
- Experimental investigation of the beam transport to the long distances;
- Transmitted force measurements.

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-type GIE.

Ion beam diagnosis in the near and far field, as well as, impulse transfer measurements have been completed at the DLR STG-ET facility.

### E. Test Results

Initial functional tests of the ITT demonstrated feasibility of all the sub-systems of the thruster. The following figure depicts ITT operating in DLR STG-ET facility on full available power during March 2016:



**Figure 6: Impulse Transfer Thruster designed and manufactured by TransMIT GmbH running in DLR STG facility. Thrust  $\approx 28$  mN; RF Power: 275 W; Mass Flow: 0.57 mg/s; Beam current: 290 mA; Drain current:  $< 2$  %; Divergence:  $< 4^\circ$ ; Total power is under 1300 W.**

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### References

- <sup>1</sup>Bombardelli, Claudio, and Jesus Pelaez. "Ion beam shepherd for contactless space debris removal." *Journal of guidance, control, and dynamics* 34.3 (2011): 916-920.
- <sup>2</sup>Merino, M., Cichocki, F. and Ahedo, E., Collisionless plasma thruster plume expansion model, *Plasma Sources Science and Technology*, 24, No. 3, 2015, pp. 035006.
- <sup>3</sup>Cichocki, F., Domínguez, A., Merino, M., Ahedo, E., A 3D hybrid code to study electric thruster plumes, *Space Propulsion Conference 2016*, paper No. SP2016-3124968.
- <sup>4</sup>Feili, D., Smirnova, M., Dobkevicius, M., Mingo Perez, A., Ruiz, M., Merino, M., Cichocki, F., Ahedo, E., "Impulse Transfer Thruster for an Ion Beam Shepherd Mission." *30th ISTS, 34th IEPC and 6th NSAT Joint Conference, Kobe-Hyogo, Japan, July 4 – 10, 2015*, paper No. C-2015-IEPC-382/ISTS-2015-b-IEPC-382.
- <sup>5</sup>Dobkevicius, M., Feili, D., Mueller, J., "Comprehensive Radio – Frequency Ion Thruster Electromagnetic and Thermal Modelling." *30th ISTS, 34th IEPC and 6th NSAT Joint Conference, Kobe-Hyogo, Japan, July 4 – 10, 2015*, paper No. IEPC-2015-410/ISTS-2015-b-410.