# Impulse Transfer Thruster – design, development and experimental characterization of the Radio-Frequency Ion Engine for contactless space debris removal

## IEPC-2025-500

*Presented at the 39th International Electric Propulsion Conference*
*Imperial College London • London, United Kingdom*
*14-19 September 2025*

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**Abstract: This paper summarises the outcomes of design, development and experimental characterisation of the Radio-Frequency Ion Engine for contactless space debris removal performed under the FP7 LEOSWEEP project: *Improving low earth orbit security with enhanced electric propulsion* (FP7/2007-2013 under grant agreement N.607457) by TransMIT GmbH. The challenging requirement set determined by the needs of long-distance impulse transfer – necessary to de-orbit or up-orbit the bulky space debris such as upper stages of launchers – drove the development of unique engine features realised in the final breadboard. An extensive experimental campaign verified full compliance with all the set performance objectives, including ultra-low angular beam divergence, thereby confirming the feasibility of the Ion Beam Shepherd concept for active debris removal.**

## Nomenclature

*DLR* = German Aerospace Centre

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*DM* = Development Model
*EGSE* = Electrical Ground Support Equipment
*FGSE* = Flow Ground Support Equipment
*FP7* = Seventh Framework Programme (European Union's Research and Innovation funding programme for 2007-2013)
*IBS* = Ion Beam Shepherd
*ICT* = Impulse Compensation Thruster
*IOS* = Ion Optic System
*ITBS* = Impulse Transfer Balance System
*ITT* = Impulse Transfer Thruster
*LDBS* = Long Distance Beam Scanner
*LEO* = Low Earth Orbit
*LEOSWEEP* = Improving Low Earth Orbit Security With Enhanced Electric Propulsion
*RIT* = Radio Frequency Ion Thruster
*TB* = Thrust Balance
*TRL* = Technology Readiness Level

## I.Introduction

LEOSWEEP stands for Improving Low Earth Orbit Security With Enhanced Electric Propulsion and assumes the concept of “contactless” Space Debris (“target”) removal based on momentum transfer via an ion beam generated by electric propulsion on a nearby spacecraft, referred to as the "shepherd." This approach enables the shepherd to interact with the debris object ("target") without physical contact, offering a potentially scalable solution for orbital debris mitigation.

The concept originates from the Ion Beam Shepherd (IBS) framework, first proposed in 2010 by the Space Dynamics Group at the Polytechnic University of Madrid[1]. A schematic representation of the IBS concept is shown in Fig. 1

**Figure 1 Schematic of the IBS.**

To maintain a constant relative position between the shepherd and the target, the spacecraft must be equipped with at least two oppositely directed thrusters:

- The Impulse Transfer Thruster (ITT), directed at the target, generates a focused ion beam to transfer momentum efficiently.
- The Impulse Compensation Thruster (ICT), oriented in the opposite direction, counteracts the recoil from the ITT, ensuring the shepherd's stability and preventing the target from accelerating uncontrollably.

This paper presents the work carried out by the TransMIT team within the LEOSWEEP project, focusing on the design, manufacturing, and testing of a Development Model (DM) of the Impulse Transfer Thruster. The thruster was developed and characterized in accordance with the significant performance and design requirements defined by the LEOSWEEP mission framework.

## II. ITT design and development

### A. Propulsion requirements

Based on the outcomes of a comprehensive mission analysis and detailed modelling of ion beam transport — both conducted within the LEOSWEEP project — a set of specific performance requirements for the propulsion system was established[2]. These requirements aim to ensure effective momentum transfer in the longitudinal direction and are outlined as follows:

- A total power budget of 3.3 kW was allocated to the spacecraft bus level (for a 545 kg platform) to support both the ITT and ICT thrusters. Considering the system efficiency of approximately 85%, this corresponds to 2.8 kW of available power at the propulsion system level.
- A minimum thrust of 30 mN on the target was determined to be sufficient to perform the planned manoeuvres of the demonstrator mission. Accounting for beam transport losses, this results in a required 31 mN thrust at the ITT output.
- To ensure effective beam coupling over the 10 m distance between the shepherd and the target, a conservative maximum beam divergence of 10° at the target was specified. Based on beam propagation studies[3], this translates into a required divergence of approximately 7° at the ITT output.
- The total mass of the propulsion system, including both ITT and ICT units, was strictly limited to less than 3.5 kg to comply with platform constraints.
- To maximize momentum transfer efficiency over the operational distance (~10 m), the ion energy must be as high as the available power allows. Simultaneously, the electron temperature should be minimized to reduce beam dispersion and power losses.

### B. Propulsion selection and optimization

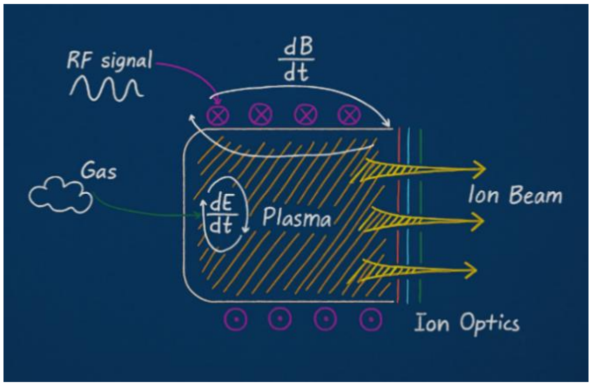

**Figure 2 Operating principle of a RIT.**

TransMIT carried out the Radio Frequency Ion Thruster (RIT) development to satisfy LEOSWEEP requirements. Such thrusters operate using an electrodeless**,** inductively coupled plasma discharge, which generates plasma without the use of internal electrodes—enhancing reliability and lifetime. Thrust is generated by extracting and accelerating ions, producing a net reaction force on the grid electrodes. A schematic of the operating principle is shown in Fig. 2.

The two primary design parameters influencing thruster performance are:

- Thruster size, which determines the maximum achievable thrust and influences both discharge power consumption and mass efficiency.
- Beam voltage, which affects ion acceleration and, consequently, the specific impulse and thrust efficiency. The optimal value of the beam voltage for the ITT is selected to ensure both low beam divergence and low power to thrust ratio, whereas power to thrust ratio is considered prevailing when it comes to ICT.

From the initial project stages, the modelling and optimization task was extended beyond the Impulse Transfer Thruster alone to include a system-level optimization of the entire propulsion subsystem, including the Impulse Compensation Thruster. Both ITT and ICT were designed using the same RIT-based propulsion technology, with the optimization process constrained by the available onboard mass and power budgets.

The detailed optimization process was presented during the IEPC 2015[4]. In the Table 1, the final modelled target performances of ITT and ICT are shown.

| **Parameter** | **ITT** | **ICT** |
|---|---|---|
| Thruster diameter | 17 cm | 14 cm |
| Thrust | 28-35 mN | 35-45 mN |
| Specific impulse | 5300 s | 3800 s |
| Power (@31mN) | < 1400 W | < 1200 W |
| Beam voltage | 3500 V | 1200 V |
| Beam current | 315 mA | 750 mA |
| Beam divergence | 5-7 ° | 26-28 ° |
| Mass flow, Xe | 0,6 mg/s | 1,2 mg/s |

**Table 1. Modelled ITT and ICT parameters.**

The grid system was selected to be flat to ensure minimal beam divergence at the target location. Whereas concave (inwardly dished) grids enable beam focusing at a defined distance from the thruster exit plane, achieving a focal length on the order of 10 meters would necessitate maintaining grid curvature tolerances within fractions of a millimeter under operational thermal loads. Such precise dimensional stability of the grid package at elevated temperatures presents significant manufacturing and material challenges, rendering dished grids impractical for this application. Consequently, a flat grid configuration was adopted to provide robust, low-divergence beam propagation over the required interaction distance.

Effective ion beam transport relies heavily on maintaining a low electron temperature within the beam, as higher electron temperatures can increase beam divergence and reduce momentum transfer efficiency. To address this, the ITT design incorporates a uniquely positioned neutralizer located centrally within the extraction area. This strategic placement aims to minimize the coupling energy of electrons by situating the neutralizer at the point of maximum electrical potential along the beam path. Additionally, this way, the neutralizer is placed in the region with the highest neutral gas density to ease plasma bridge formation and maximize charge neutralization efficiency. Together, these factors reduce electron temperature, enhance beam collimation, and improve overall thruster performance.

To meet the beam divergence requirements, the grid system was numerically simulated to optimize the geometry of a single aperture capable of accommodating the specified extraction voltage and ion current, as defined during the thruster optimization process. The plasma parameters used as input for this simulation were derived using the Comprehensive Radio Frequency Ion Thruster Electromagnetic Model[5]. This model was also employed to inform the design of the discharge chamber geometry and to support the selection and shaping of the corresponding RF circuit.

### C. ITT design

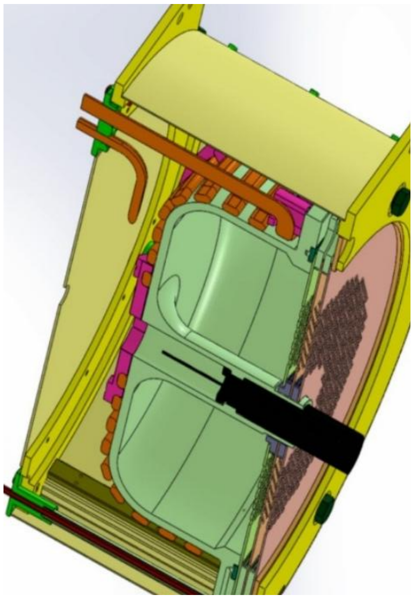

**Figure 3 ITT design cross-section**.

Based on the outcomes of the system optimisation, key design decisions, and preliminary modelling efforts, a comprehensive thruster design was developed (Fig. 3).

The system is composed of the following main sub-assemblies: ionizer, ion optic system (IOS), high voltage and propellant feed interfaces and structural support. Each sub-assembly presented distinct design challenges and functional requirements, which are discussed below.

The ionizer comprises the discharge chamber, RF coil, and associated mechanical mounting. As the decision has been taken to introduce electrons in the axis of the beam, the discharge chamber design came out comparably complex, accommodating an intermediate volume with a flange where a built-in or specially designed neutralizer could be attached. Three options discussed at the time were the following:

- Introduction of the feed line at the back of the central compartment and dedicated extraction electrode in its frontal part, with utilisation of the common RF-circuit to generate plasma in both toroidal ion thruster discharge volume and central dedicated RF-neutraliser volume.
- Introduction of the micro apertures to the walls of the central compartment with simultaneous closure of the back of the central compartment, in which way the thruster feeding line would deliver propellant to both the main ion thruster discharge volume and central neutralizer volume. The pulsed electron extraction was to be used for this option.
- Classic hollow cathode neutralizer designed for operation within the ion thruster discharge chamber.

Separate Radio Frequency Neutralisers were opted out completely, as in this case, thruster and neutralizer electromagnetic designs would be in great conflict, and the overall system efficiency would inevitably be compromised.

**Figure 4 RFG250 DM**.

The option of a dedicated neutralizer was considered the lowest risk given the number of other not proven priorly design solutions were already suggested for project execution. The heaterless hollow cathode neutralizer capable to withstand positioning inside the discharge chamber of an ITT was developed by the longstanding partner of TransMIT – Prof. Andrey Loyan in Kharkiv Aviation Institute[8].

Once the full-sized design of the discharge chamber was prepared, comprehensive plasma modelling was performed to optimize the final geometry of the Discharge Chamber and the Coil to minimize RF power and smooth the plasma properties in the near grid area. The requirements

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[8] Nowadays Prof. Loyan works continue in TIGBIS[6].

for RFG were also derived at this stage, and the dedicated hardware – RFG250 DM shown at Fig. 4- was developed and manufactured by APCON GmbH. Further, particular attention was then given to the thermal design of the discharge chamber and co-engineering of the thermal interfaces between the ionizer and the neutralizer.

The IOS is a multi-electrode assembly responsible for the electrostatic ion extraction, acceleration and beam formation. All the essential thruster parameters, including Thrust, Specific Impulse, divergence and Lifetime, are highly interdependent with the operational condition and design parameters of the IOS. The initial design phase focused on optimising the single-aperture geometry, based on the plasma parameters derived from the discharge chamber modelling and fixed voltage settings. Key grid design parameters — including aperture diameter, inter-grid spacing, and grid thickness — were selected with the primary goal of achieving minimal beam divergence while maintaining structural integrity and electric field uniformity.

Once the desired single-aperture behaviour was achieved, a macroscopic grid layout was developed. However, due to the inherently high thermal loads with high gradients experienced during operation, the Ion Optics System requires careful attention to thermo-mechanical stability. These thermal effects can result in grid deformation, which may disrupt the precise inter-grid spacing and aperture alignment required for stable thruster performance. Any deviation in the relative positioning of the grids can lead to beam instability, increased erosion, or system failure.

To address these challenges, an iterative thermal and mechanical modelling was conducted. This modelling guided the selection of suitable materials and the structural design of the IOS components to ensure their dimensional stability under the expected thermal loads and plasma exposure throughout the mission duration.

The finalized Ion Optics System employs a three-grid, carbon–carbon flat assembly, selected for its high thermal stability and erosion resistance. A floating seal mechanism is implemented at the grid edges to accommodate thermal expansion and mechanical tolerances while maintaining leak-tight integrity of the thruster interior and electrical isolation.

A significant additional complexity arose from the central placement of the neutralizer, which necessitated the inclusion of a central aperture in each grid. This central feature also required its own floating seal to ensure proper alignment and maintain the functionality of the entire IOS under thermal cycling conditions.

High-voltage interfaces include electrical feedthroughs and insulation elements to supply and isolate the grid voltages. To allow free grid expansion, spring pushed electrical contacts were specially designed. Three SHV connectors were used on the thruster back flange for harness connection.

Total size of ITT DM is 26cm*22cm*17cm (including the Neutralizer installed). Mass of the thruster is under 5300 g. Both mass and size have sufficient margin for later reduction, given the low TRL of the ITT. Figure 5 depicts the ITT DM hardware.

**Figure 5 ITT DM**.

## III.Experimental setup

To validate the previously derived analytical and numerical models related to ion beam physics and beam–target interactions, a comprehensive performance characterization test campaign was conducted on the developed Impulse Transfer Thruster. This testing aimed to confirm theoretical predictions experimentally and to quantify key operational metrics under controlled conditions. Test activities took place from October 2015 to March 2016 and comprised ITT functional and performance testing and ITT beam transport investigations, including transmitted force measurements.

The first phase of testing was conducted at the Thermal Vacuum Facility of the David Fearn Electric Propulsion Laboratory, University of Southampton[10]. These tests were carried out in a clean, high-vacuum environment, targeting validation of the thruster's predicted operational behaviour and evaluation of its compliance with the LEOSWEEP system requirements. The activities included functional tests where all thruster voltages, currents, powers, and mass flow rates were measured to characterize the thruster operating range via indirect thrust measurements. Thrust was calculated to high accuracy consistent with established methods for Gridded Ion Engines.

Subsequent testing, including detailed ion beam diagnostics and impulse transfer measurements, was performed at the DLR STG-ET facility[7]. These investigations addressed both near-field and far-field beam characteristics, contributing to a refined understanding of beam propagation, divergence, and momentum transfer efficiency — all critical factors in validating the ITT's applicability to active debris removal and other in-space applications.

### A. Thermal Vacuum Facility of Southampton University and ITT's initial characterization test setup

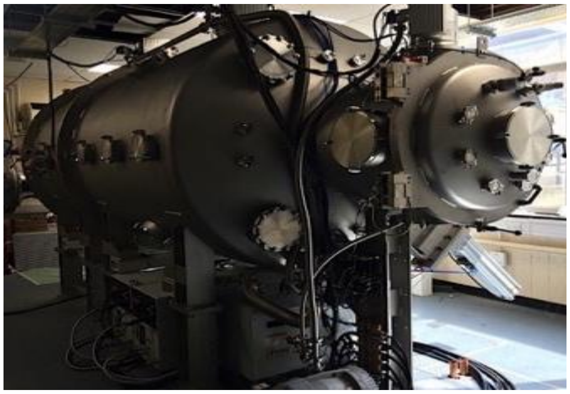

**Figure 6 Thermal Vacuum Facility of the David Fearn Electric Propulsion Laboratory, University of Southampton, UK**

University of Southampton Thermal Vacuum facility depicted at Fig 6 consists of a main chamber and a hatch, separated by a high-vacuum gate valve, with a total volume of about 5,4 m³. The main chamber is approximately 1.9 m in diameter and 4 m in length, while the hatch provides an additional cylindrical volume with a diameter of 0.75 m.

The double-stage pumping system combines turbomolecular and cryogenic stages, providing a total pumping speed of about 35,000 l/s and achieving base pressures as low as $10^{-8}$ mbar without propellant flow. During thruster operation with standard flow rates, chamber pressures of $2 \times 10^{-5}$ mbar were maintained, which are representative of typical ion thruster test conditions.

The Facility is equipped with a fully autonomous control system that includes chamber pressure monitoring. A water-cooled carbon beam target is located at the main chamber door surface. It is positioned at 60° relative to the thruster axis to reduce back-sputter towards the ion optics. The ITT was mounted in the hatch and operated into the main chamber towards the target; its operating parameters were continuously monitored by dedicated ground support equipment.

### B. DLR STG-ET facility and ITT beam characterization setup

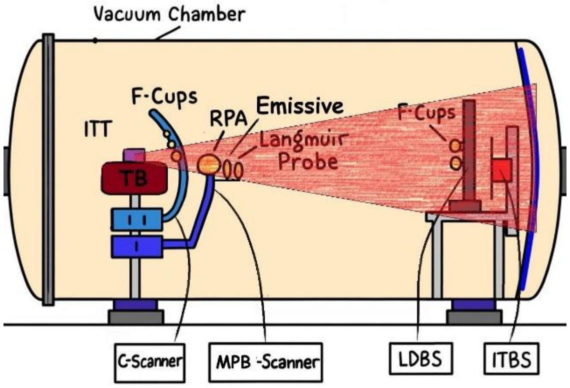

**Figure 7 STG-ET test setup**

The STG-ET test facility of DLR is a single-volume 12m long and 5m diameter vacuum chamber.

The double-stage pumping system combines turbomolecular pumps for reaching static vacuum and stand-by operation and up to 10 cryopanels to secure low dynamic pressures, achieving base pressures as low as $10^{-8}$ mbar without propellant flow. Chamber pressures of under $2 \times 10^{-5}$ mbar were maintained throughout ITT operation. A windmill-shaped beam damp is mounted at the rear wall of the facility. Further details on the STG-ET facility, including the description of ion beam diagnostics and thrust balance, can be found in ref. 7.

Fig. 7 depicts a schematic of the test setup for ITT beam characterization. During the beam characterization test campaign, the ITT was mounted on the STG-ET thrust balance (TB) and operated into the main chamber toward a carbon beam target. The C-scanner with 15 Faraday cups located at 0,7 m distance from the thruster exit was used to determine beam divergence in the near field. Multi-Purpose Beam Scanner (MPB-Scanner) carried RPA, Emissive and Langmuir probes for determination of the space potential, electron temperature in the beam and ion energy. The Two-dimensional Long Distance Beam Scanner (LDBS) with two Faraday cups were used to determine beam divergence in the far field at a 6,2 m distance from the thruster exit. The Impulse Transfer Balance System (ITBS) with the 60 cm circular target was used to measure the Ion Beam force transferred to the far field to support LDBS measurements.

### C. ITT ground support equipment

The ITT Electrical Ground Support Equipment (EGSE) supplied electrical power to the experimental setup and its control. The command of the devices and the acquisition of measurements were implemented by computer software.

Network access enabled remote operation, allowing work away from the noisy environment around the vacuum chamber. Physical access to the EGSE-rack enabled manual override of nearly all remote and software actions in case of necessity.

The physical composition of the EGSE can be seen in Fig 8. All components were placed inside a 19-inch rack and connected via Ethernet or RS232 to the control unit. On the backside, an interface panel provided easy connectivity for the external components of the experimental setup.

**Figure 8 FGSE (left) and EGSE (right)**

For the testing of the ITT development model, a laboratory gas flow control system was used. The Flow Ground Support Equipment (FGSE) was placed outside the vacuum chamber and was built up with conventional commercial parts. Figure 8 depicts FGSE hardware.

The FGSE was supplied with the propellant from a bottle with an attached pressure-reducer through an input isolation valve. Two separate flow branches controlled the gas flow to supply both the thruster and the neutraliser. Bronkhorst flow control units were used to control the mass flow in both branches, and every branch was equipped with two isolation valves: one manual and the other electric. All the elements of the FGSE were controlled by the EGSE.

## IV.Results

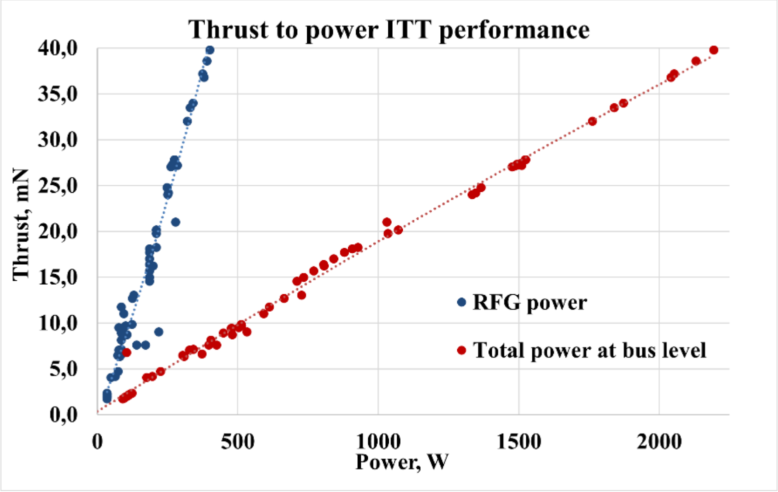

**Figure 9 ITT thrust per power performance**

Figure 9 presents the experimentally derived thrust-to-power performance of the Impulse Transfer Thruster. The measured power consumption at the thruster level remained within 3% of the projected design values, confirming the accuracy of the pre-test performance estimates. Furthermore, the ITT successfully demonstrated the entire required thrust range, validating its capability to meet mission-specific propulsion requirements.

The ITT maximum thrust would also be compliant with the demonstration mission concept of JPL NASA for the deflection of the 2004 JN1 asteroid[8]. Although the ITT would require around 40% higher power than the Halo 12 hall effect thruster selected by NASA, it could deliver almost three times the specific impulse, and thus reduce the necessary propellant amount drastically.

The exemplary beam profiles in the near and far field at the nominal LEOSWEEP operating point are shown on the Fig. 10 below.

As shown in Fig. 10, the near-field ion beam profile exhibits an unnaturally flattened central region, attributed to the probe saturation during measurement. This saturation leads to slight inaccuracies in post-processed data, resulting in a moderate overestimation of the near-field beam divergence. It is also important to note that, in this specific test configuration, a meaningful assessment of the near-field divergence must consider the geometric relationship between the thruster's extraction area and the distance to the C-scanner. These two dimensions are of the same order of magnitude, which significantly influences the apparent measured beam spread in the near field. Another observation worth noting was that the beam divergence was visibly changing (increasing) when the C-scanner entered the beam, and especially with the scanner arm moving towards the central axis. Some of the post-processed data show non-symmetry of the profile that might be associated with this effect (Fig. 11).

For the nominal operating point, a 95% beam envelope divergence of 4.10° was measured in the near field, while a divergence of 4.61° was determined in the far field. These results show slower growth of the beam divergence in the

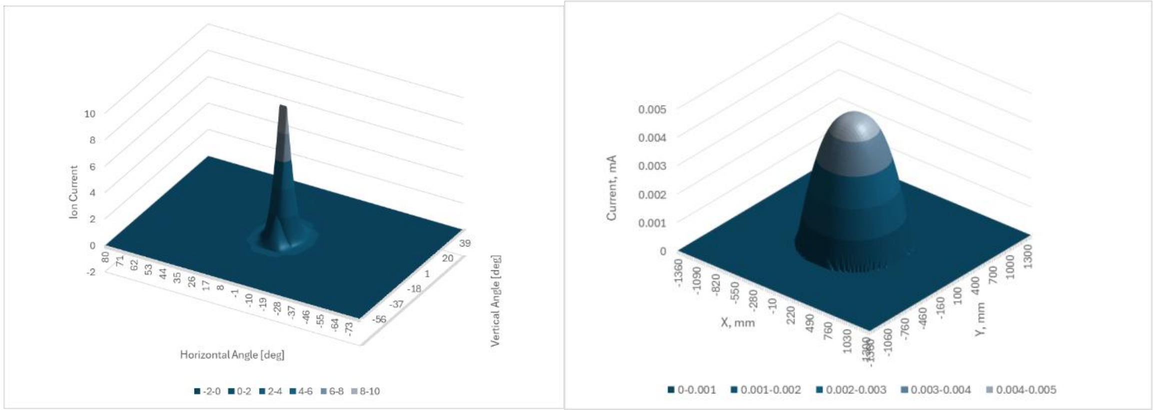

**Figure 10 ITT near (left) and far (right) field current profiles measured at DLR STG-ET.**

far field that was estimated during project execution[3], given the expected beam collimation characteristics, and confirm that the ITT maintains low-divergence performance at the far field, enabling the Ion Beam Shepard concept.

Since the ITT was equipped with a three-grid system isolated from the thruster case, the opportunity was taken to perform beam measurements with redistributed potential within the grid system to mimic the four-grid system behaviour, which would be the first known to the authors' operation of a large ion thruster in full scale with this specific feature. The extraction potential difference was set to the same total value as that at the nominal operating point of the ITT thruster, while the potential of the first grid was reduced almost by half.

In this case, the near-field beam divergence was observed to increase by approximately 1° compared to a conventional three-grid extraction system operating at the nominal ITT voltage, reaching a value of 5.05°. This moderate increase in divergence remains within acceptable performance margins and is attributed to the specific beam shaping characteristics of the four-grid configuration, likely not reachable with this energy in classic potential distribution scenarios.

In contrast, the impulse transfer efficiency—evaluated via the force imparted to the ITBS target—revealed a significant dependency on ion energy. Specifically, thrust transfer efficiency was reduced more in the low-energy ion case compared to the high-energy configuration, where momentum coupling was substantially more efficient. This highlights the importance of ion energy optimisation in maximising impulse transfer for contactless actuation scenarios.

However, the ability to modulate beam shape by the potential redistribution within the Ion Optic System could be further exploited, particularly in the active debris removal or asteroid deflection scenarios. Independent regulation of the ion energy significantly impacts the efficiency of the beam transfer into the far-field. Combined with the precise selection of the optimal extracting potential difference, which shapes the plasma meniscus and allows the beam to reach the lowest divergence possible, this could become a perfect technique to implement this type of mission.

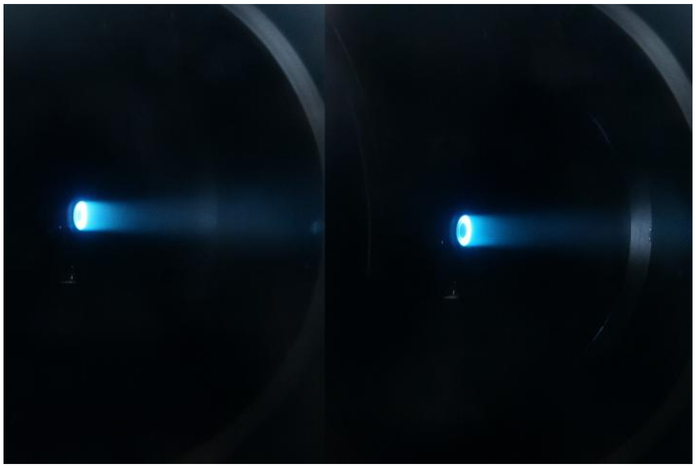

**Figure 11 ITT thrust per power performance**

## V.Consecutive study

In parallel with the main LEOSWEEP activities, work on the Double-Sided Thruster (DST) concept for IBS missions was performed. This thruster produces two ion beams from the same discharge chamber: the beam from one side of the thruster is used for the ITT, while the beam from the other side is employed for the ICT. Therefore, instead of a two-thruster design, a single double-sided thruster that simultaneously produces two ion beams can be used. The main advantage of such a design is a much simpler sub-system architecture, lower cost, similar or lower propellant mass required and lower total mass, with the total power similar to that of a two-thruster system. Further details on this breadboard development and testing can be found in ref. 9.

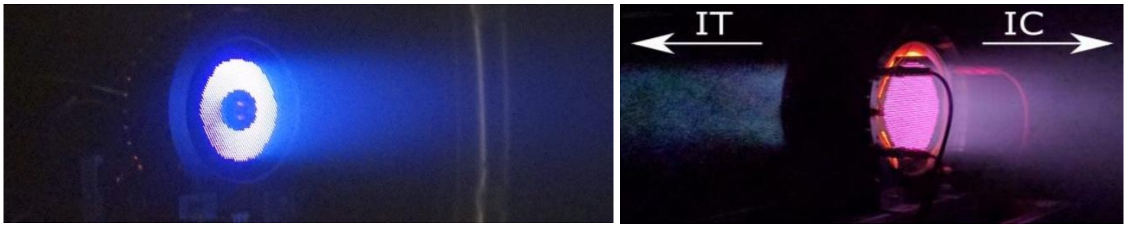

**Figure 12 ITT running in DLR STG-ET facility (left) and DST running in Southampton University (right).**

## VI.Conclusion

Figure 12 depicts the ITT in operation in the DLR STG-ET facility and DST in operation in the Thermal Vacuum Test Facility of Southampton University.

The design, development and testing of the Impulse Transfer Thruster under the LEOSWEEP project have demonstrated that a Radio-Frequency Ion Engine can meet the demanding requirements for contactless momentum transfer in active debris removal missions. The ITT achieved thrust levels, power efficiency, and ultra-low beam divergence consistent with the mission needs, validating both the design methodology and supporting plasma and beam transport models.

The ITT design comprised multiple unique features and concepts never employed for a GIE before such as a toroidal discharge chamber with a dedicated central neutralizer space, three-grid system with floating seals both at the outer and inner edges, four-grid (with fourth grid represented by encircling ring on thruster output) mode successfully demonstrated in the full-scale thruster for the first time to the authors' knowledge. Characterisation of those features suggests that the Impulse Transfer Thruster, when combined with an accurate beam control and optimised ion energy, could serve as a highly effective and scalable technique for enabling contactless momentum exchange. As such, it holds significant promise for making advanced mission concepts—such as active debris removal and asteroid deflection—technically and operationally feasible in the near future.

The experimental campaigns at Southampton University and DLR confirmed reliable operation under representative vacuum conditions and showed that impulse transfer efficiency strongly depends on ion energy optimisation. The successful reproduction of the predicted performance metrics reinforces the feasibility of the Ion Beam Shepherd concept for large-scale orbital debris mitigation and potentially for planetary defence scenarios such as asteroid deflection. For the latter case, ITT seems to be fitting well with the requirements of the NASA demonstrator mission for the deflection of the 2004 JN1 asteroid.

Beyond validating a two-thruster configuration, the exploratory work on the Double-Sided Thruster (DST) suggests a promising avenue for simplifying system architectures and reducing overall mass and cost.

Future efforts should focus on maturing the ITT-based propulsion system to higher Technology Readiness Levels.

These advancements collectively underscore the importance of precise beam control and system-level optimisation in enabling scalable, non-contact solutions for maintaining orbital safety and advancing future space operations, aligning with the Zero Debris initiative[11].

## Acknowledgments

The majority of the results presented are financed under grant agreement N.607457 FP7 LEOSWEEP project: *Improving low earth orbit security with enhanced electric propulsion* (2007-2013).

The authors would like to acknowledge the inputs of Prof. Horst Löb, with whom they had the great pleasure of discussing the design choices as well as the experimental outcomes of this activity.

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