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Update on diagnostics for DLR‘s Electric Propulsion Test Facility

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Abstract

DLR has operated since the end of 2011 a dedicated electric propulsion (EP) test facility, the High Vacuum Plume Test Facility Göttingen – Electric Thrusters (STG-ET). This EP test facility has now accumulated several years of thruster testing experience. Special features characterize this facility tailored to electric space propulsion testing. In the first place, a large vacuum chamber mounted on a low vibration foundation characterizes the facility. A performant pumping system ensures a good vacuum, and a target with low sputtering coating dumps the beam power. The vacuum chamber is 12m long and has a diameter of 5m. With respect to thruster tests, the design focus is on accurate thrust measurement, plume diagnostics, and plume interaction with spacecraft components. Electric propulsion thrusters have to run for thousands of hours, and with this the facility is prepared for long-term experiments. The present paper gives an overview of the facility, and describes the vacuum chamber, pumping system, diagnostics, and experiences with these components. After commissioning of STG-ET, the main focus was put on the testing of Hall-effect and gridded ion thrusters.

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Keywords: electric space propulsion; vacuum chamber; ion beam; diagnostics; ground test facility

Nomenclature

DLR	Deutsches Zentrum fuer Luft- und Raumfahrt (German Aerospace Center)
EP	Electric Propulsion
STG-ET	Simulationsanlage Treibstrahlen Göttingen – Elektrische Triebwerke
RIT	Radiofrequency Ion Thruster
RPA	Retarding Potential Analyzer

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1. Introduction

Electric space propulsion is nowadays used routinely for satellite station keeping. Recently, a activities began to use electric propulsion also for orbit transfer. All-electric satellites will ultimately perform these manoeuvers, and consequently will need higher thrust engines. Electric propulsion is also gaining more interest in the sector of future science missions requesting very low thrust in conjunction with low thrust noise and accurate thrust level control. On the other hand, electric propulsion (especially ion thrusters) comes with low absolute thrust compared to thruster mass, and this requires long runtimes for fulfilling a given mission. This implies special challenges for qualification and on-ground testing, which means that EP testing sets very different boundary conditions to test facilities compared to chemical propulsion.

The German Aerospace Center DLR has about 8000 employees working in its 16 sites spread over Germany (see Fig. 1). Based on the above mentioned perspective of EP growth the DLR Göttingen site added to its chemical space propulsion testing capabilities a test facility for electric propulsion, the STG-ET (Simulationsanlage Treibstrahlen Göttingen – Elektrische Triebwerke).

The inauguration of the facility took place at the end of 2011, and soon after final commissioning the facility has been used for operating electric thrusters. Fig. 2 shows a view into the open vacuum chamber of the STG-ET facility. In parallel additional infrastructure and diagnostics elements have been added step by step. The next sections provide an overview of the vacuum chamber and the installed diagnostics [1].

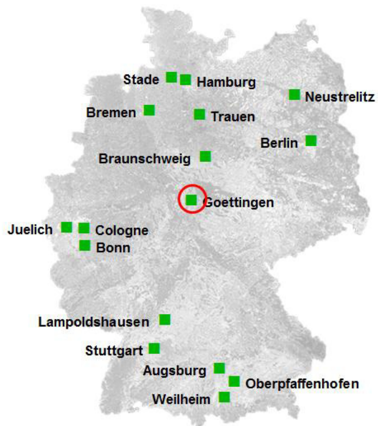

Fig. 1: DLR sites across Germany. The Electric Propulsion Test Facility is located in Göttingen (circle in red)

Fig. 2: DLR Test Facility STG-ET with open vacuum chamber

2. Facility Vacuum Chamber

The central element of the facility is a 12m long and 5m diameter vacuum chamber. Fig. 2 shows the facility with its door open. For instrumentation and pumping 169 feedthrough ports are available.

The chamber is mounted on sliding bearings for reduction of stress in case of pump-down and temperature changes, both of these will change the chamber geometry. Test object and diagnostics equipment are positioned on a stand which is decoupled from the metal chamber wall. This decoupling ensures less vibrations and a well-defined space coordinate system origin.

The STG-ET is located in close vicinity to other DLR space vacuum test facilities and shares a common infrastructure of cryogenic media including liquid nitrogen and liquid helium. In order to operate electric space thrusters in a vacuum chamber, powerful pumps are required to keep a low and space-like background pressure. As in other facilities DLR's vacuum chamber uses cryopumps when running EP thrusters. Rough vacuum is achieved with rotating vane and Roots pumps, while high vacuum for standby operation it reached with turbo pumps. Up to 10 cryopumps are in operation when thrusters are running. Typically the EP thruster operational pressure ranges from $1 \cdot 10^{-5}$mbar up to $4 \cdot 10^{-4}$mbar, depending on manufacturer requirements. The standby pressure is in the 10^{-8} mbar range.

Checks for all pressure gauges are very important for a facility expected to operate at high standards. Therefore, we have a pressure sensor calibration stand which is able to simultaneously compare up to 5 gauges with a reference gauge in the range 1000mbar to 10^{-7} mbar.

For thruster preparation and handling a cleanroom tent is available of class ISO 8 with a size of 2m by 3m by 3m.

Ion thrusters expel beams of fast ions that may interact with the facility walls and equipment. These high velocity ions cause sputtering when hitting the walls of the chamber or all other components located inside the chamber. In ion propulsion test chambers dedicated beam dump targets are used for reduction of sputtering effects. Such a component has also been installed in the DLR facility. The beam dump must successfully minimize the possible sputtering, and must be able to dump the heat flux generated by a wide range of EP thrusters including the most powerful ones. A windmill-like design was chosen because it leads to a more symmetrical behavior compared to venetian blind designs used in other EP test facilities.

3. Thrust Balance

The STG-ET with its large vacuum chamber was designed such that thrusters with high thrust of up to several hundred mN can be tested [1]. In future, an upgrade for thrusters generating thrust up to 1N is foreseen. Thrust measurement is an important task to be performed on all types of thrusters. The challenge in electric propulsion is that thrust values are very small compared to the weight of a thruster. DLR has a thrust balance which is an actively compensated inverted double pendulum design [2]. This design has proven to be very sensitive [3].

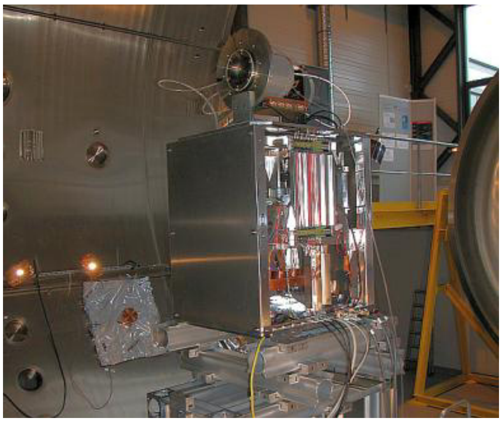

Fig. 3: DLR thrust balance installed in the vacuum chamber with a RIT mounted on top

Fig. 3 shows the open DLR thrust balance and a gridded ion thruster of RIT type mounted on it. This balance can carry a single thruster or arrays with a mass of up to 40kg. To minimize hysteresis or other unwanted force effects, cables and pipes feeding the thruster are routed in a holder configuration called ‘cable harp’. Herein the lengths of cables and tubes are adjusted so that the distance between their bending points is the same as between corresponding balance pivoting bearings.

Calibration is important and therefore the thrust balance has two independent methods for performing a calibration. First, there is a voice coil calibration, and second a gravimetric calibration. The voice coil method uses a calibrated coil to apply a known force to the balance platform. The gravimetric method is based on accurately measured masses for a direct calibration. Their weight forces are applied to the thruster platform by a thin wire guided over a pulley. While the voice coil method is more flexible and faster, shows smaller variances and allows a larger number of measurement points compared to the weight calibrator, systematic errors might occur. On the other hand, the gravimetric method can be traced back to absolute standards as it is based on an accurate weight measurement.

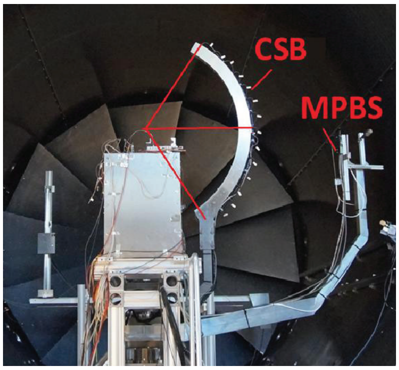

Figure 4: C-shaped scanner CSB and multipurpose scanner MPBS in the STG-ET.

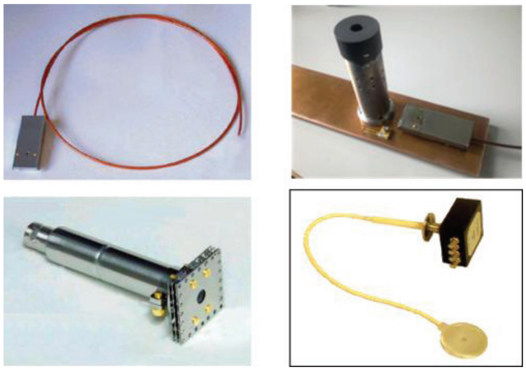

Figure 5: Various ion detectors: Faraday cups and RPA (lower right).

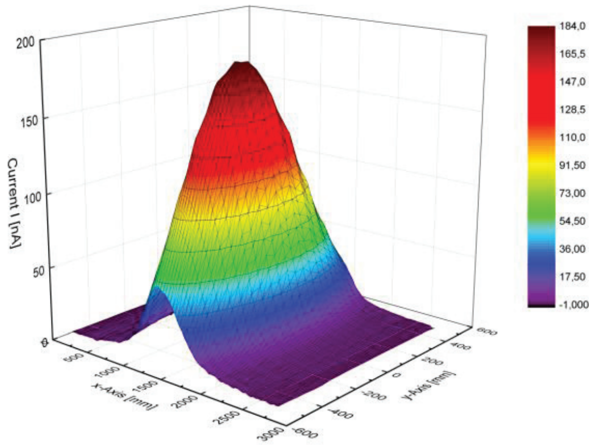

Fig. 6: Beam shape recorded with the LDBS

4. Thruster Beam Diagnostics

Ion beam diagnostics is besides thrust measurement the other important task in the field of EP testing. For that purpose two rotational scanners are implemented in the STG-ET [1]. Figure 4 shows the two systems, the multi-sensor arm CSB and the multipurpose arm MPBS) that enable recording of ion current distributions at a distance of 0.7-1.5m from thruster exit. The maximum scanning speed is 2deg/s for the single plane arm, and up to 10deg/s for the multi-sensor arm. The multi-sensor arm is permanently equipped with 15 Faraday cups, while the single plane arm has the capability of carrying different sensor types. Several available sensors are shown in Figure 5. The standard setup for the single plane arm uses two Faraday cups and one retarding field energy analyzer (RPA).

For measurements at longer distances from the thruster exit (2-7m) a system called Long Distance Beam Scanner (LDBS) is available. This is a flat-field scanner with 2 linear rails, and a scanning area of 3m horizontal and 1m vertical. Fig. 6 shows a measurement recorded with the LDBS. At that distance the beam has easily several meters of diameter.

When investigating the impact of a thruster plume on spacecraft components the beam divergence is an often used parameter. Simply speaking, the divergence β can be deduced by using the beam size A (radius) and the measurement distance D, as depicted in Fig. 7:

$$\beta = \arctan\left(\frac{A}{D}\right) \tag{1}$$

This approach is only valid if the thruster exit can be regarded as a point source. If the source extension is not negligible compared to the distance D, the determination of beam divergence is different, as shown in Fig. 8. One can see that even in case of a perfectly parallel beam without divergence and with a beam size B at distance D would give a beam divergence greater than zero ($\delta \neq 0$). A better formulation of beam divergence would be:

$$\beta = \arctan\left(\frac{A-B}{D}\right) \tag{2}$$

Here B is equal to the thruster exit radius R_{th}. From a measurement point of view A is the beam extension defined by capturing 95% of total beam flux. This is a quantity that can be collected by processing data.

Other plasma parameters like electron temperature or plasma potential can be measured with emissive or Langmuir probes. Fig. 9 shows the MPBS arm with these two probes mounted.

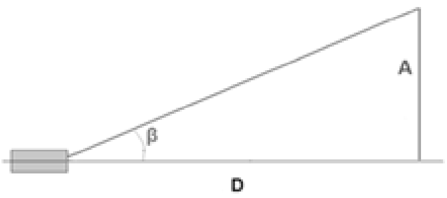

Fig. 7: Simple point source approach for beam divergence

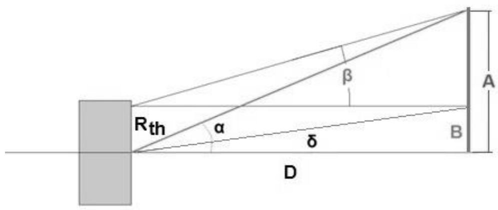

Fig. 8: Beam divergence in case of an extended source

Fig. 9: Multipurpose scanner MPBS with emissive and Langmuir probes

5. Thruster Operation

Since 2012, after the inauguration of the STG-ET facility, testing of thrusters started. Fig. 10 shows three different thrusters running in the STG-ET. DLR's own test thruster is a RIT10 radiofrequency source with aperture exit grids containing 37 extraction holes. The grid setup of this so-called RIT10/37 produces a narrow, low divergence beam (see Fig. 10, left). A control system for this thruster was developed by DLR, and the thruster has been used many times for qualification of the above mentioned beam diagnostics, and for the investigation of facility modifications. The more powerful Airbus Safran Launchers thruster RIT22 was also under test (see Fig. 10, center). This showed that the facility is able to handle more powerful thrusters up to about 5kW. Fig. 10, right, pictures the operation of a Hall-effect thruster of PPS®1350 type by Snecma (renamed Safran Aerospace Engines since 2016). The operation of these different thruster types shows the flexibility of the facility.

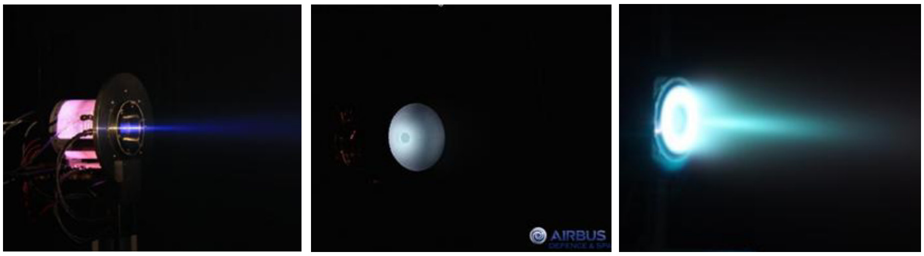

Fig. 10: Thrusters in operation in the STG-ET (left: DLR RIT10; center: RIT22, courtesy Airbus; right PPS®1350, courtesy Safran-Snecma)

6. Conclusion

DLR's EP test facility was inaugurated in October 2011, and started operation in 2012. Since then, tests on different electric propulsion thrusters have been performed. The pumping system was modified a few times, and will be upgraded soon. A custom-made thrust balance offers online thrust measurements. This complex device will be modified and improved step by step for reaching higher accuracy and better performance. Different beam profile scanners are available that can retrieve beam scans at various distances from the thruster exit, and enable beam divergence measurements.

Acknowledgements

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