The New DLR High Vacuum Test Facility STG-ET

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Abstract: At its Göttingen site the German Aerospace Center DLR extended its activities beyond chemical space thrusters to electric propulsion. This type of engine is gaining more interest especially in the sector of micropropulsion as several future missions request very low thrust coupled with very accurate thrust level control. DLR is building a new vacuum chamber facility, named STG-ET, especially for electric propulsion testing. Its vacuum chamber measures 12.2 m in length and 5 m in diameter. The focus will be on plume interaction with spacecraft components and on long-term tests. The facility will be equipped with advanced measurement methods for plasma analysis and thrust vector measurement. This paper describes the technical features of the facility and the scope of its application.

Nomenclature

CEX:	Charge Exchange Particles
DLR:	Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center
EP:	Electric Propulsion
ET:	Elektrische Triebwerke, Electric Thrusters
HEMP:	High Efficiency Multistage Plasma
LHe:	Liquid Helium
LN2:	Liquid Nitrogen
RIT:	Radiofrequency Ion Thruster
RTD:	Temperature Dependent Resistor
SPT:	Stationary Plasma Thruster
STG:	Simulationsanlage Treibstrahlen Göttingen

I. Introduction

Plume flow and plume impingement of chemical and cold gas thrusters are subject of research and application at the German Aerospace Center DLR in Göttingen since about three decades [1]. Within this activity DLR has built and is operating the unique High Vacuum Plume Test Facility STG (in German: Simulationsanlage für Treibstrahlen in Göttingen). Figure 1 shows this facility with open chamber door and the inner cold walls and cryopumps can be seen. The STG has a liquid helium-driven cryopump. With an area of about 30m² it completely encloses the cylindrical test section with a length of about 5m and a diameter of 1.6m. The temperature of the cryopump of only 4.3 K allows pumping all exhaust gases except helium at pressures below 10^{-7} mbar (or about $3{\cdot}10^{-6}$ mbar if H_2 is present). Thus plumes from small thrusters can freely expand just as in space vacuum. This unique ability enables investigations of plume spreading and impingement under space-like vacuum conditions.

A few years ago DLR decided to add electric propulsion to its low thrust engine investigations. As electric propulsion also means longer runtimes and additional critical plume-spacecraft interactions, these topics had to be added to the test capability portfolio.

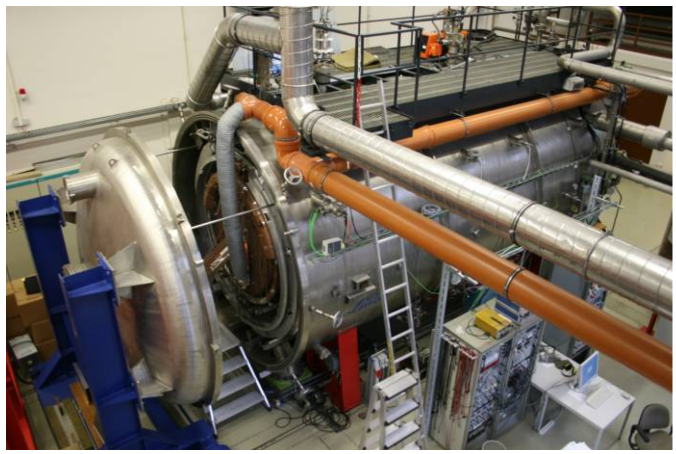

Figure 1: Test chamber for chemical thruster tests STG at DLR Göttingen. The chamber is open and the front panel of the LHe cryopump can be seen.

A study to explore the options of extending the usage of the available STG to electric thrusters has been previously performed. Unavoidable sputtering of the cupreous cryopump surfaces used for chemical thruster investigations however would result in an inacceptable high copper deposition on the thrusters under test and in destruction of the cryopump. Alternating use of the available cryopump for chemical thrusters and a new cryopump/target-arrangement suitable for electric thrusters turned out to be inappropriate because of time and effort required to switch between operating modes.

The best solution was found to be an ensemble of two separate vacuum chambers which share the available liquid helium infrastructure. While geometric restrictions would have to be accounted for when extending the available STG, the construction of a separate chamber permits matching the design to the specific requirements of this application. In this paper we present the details of planning and design of the facility and its present state of assembly and operation.

II. Characteristics of low thrust chemical and electric propulsion

Low thrust propulsion is used for attitude and orbit control as well as for cruising and covers mainly the thrust range from a few milli-Newton to some hundreds of Newton. Both types of propulsion chemical and electric have the same purpose: production of thrust. Testing and characterization however requires different test facilities.

The achievable high exit velocities in electric propulsion lead to higher efficiencies in view of propellant consumption compared to chemical propulsion which must be bought by an additional energy supply system on board.

When thrusters on a spacecraft are fired it inevitably comes to plume impingement. In chemical propulsion disturbing and undesired forces and moments, heat load, and contamination are effects to be dealt with. In electric propulsion moreover the destructive impact of the high energy ions and the electric interaction between plume and spacecraft can cause severe problems.

To simulate space environment for chemical and electric propulsion and especially plume testing best vacuum conditions, say < 10^{-5} mbar, are crucial. For electric propulsion in addition the approach to simulate space conditions is made difficult by different electric interactions plume/spacecraft and plume/facility, which can be reduced by using a large vacuum chamber.

These kind of propulsion systems are usually intended to operate over long periods, but the accumulated firing times are quite different for chemical and electric thrusters. A set of 10N chemical thrusters used for attitude and orbit control with a propellant supply of about 100 kg has an accumulated firing time of about 10 hours. The mission firing time of a single electric propulsion engine may be of the order of $t_{mission}$=10,000 hours. This means that ground qualification tests have different aspects. For electric propulsion they must give proof of a longer test period. A typical qualification test safety factor is 1.5 [2, 18]:

$$t_{qualification} = 1.5 \cdot t_{mission} = 15000h$$

Tests can be extended to 20,000 hours in order to simulate orbit transfer manoeuvres [18]. Furthermore it is important to be able to perform lifetime testing on a system scale. Usually the engines are run in cycles, e.g. a few hours on-time and about a day switched off. Such cycles can be simulated but it is preferable to shorten the process in reducing the off-time to about one hour. Another requirement for qualification testing is the cold start of the engines beginning at low temperatures of e.g. -85°C [18].

Testing in electric propulsion requires vacuum of < 10^{-4} mbar or even <10^{-5} mbar, dependent on the thruster type, while about 10^{-1} mbar are in many cases sufficient for testing chemical thruster behaviour before background gas influences the performance of a thruster due to causing flow separation at the nozzle exit.

However to perform investigations of undisturbed plumes as in space requires in any case a vacuum of <10^{-5} mbar, otherwise the barrel shock terminates the free expansion in chemical propulsion. In electric propulsion the plasma properties can be falsified, for example by an increased rate of CEX-particles [3].

Another difference results from the typical thrust ranges of small chemical and electric thrusters. In general, electric propulsion engines generate lower thrust values. These much smaller forces require more sensitive thrust measurement equipment, which in turn is more sensitive to external disturbances.

III. Facility Requirements

To complete DLR’s expertise in plume investigation, vacuum and cryo technology by the necessary EP-competency the company “Dr. Harmann Technologieberatung” (HTC) has been appointed by DLR in 2009 for designing and engineering tasks and to develop the facility. HTC is well-experienced in EP-testing [9-17], facility construction [5, 6], and thruster development [12-16]. In close cooperation the following characteristics of the new EP-facility and its requirements were elaborated:

1. The test facility is suitable for plume-, plume impingement-, and lifetime-tests for thrusters with up to 25kW.
2. Provision of highly sensitive measurement equipment (i.e. there are small systematic disturbances caused by the facility and its surroundings) suitable for ion beam profile measurements also in the backflow, thrust and thrust-vector measurement, lifetime measurement.
3. Provide as large as possible distances between thruster and vacuum chamber walls to minimize sputtered materials density and minimize electric interaction with chamber walls.
4. Provision of continuous pumping speed of 200,000 l/s to allow background pressures <10^{-5} mbar for thrusters with mass flow up to 100 sccm Xe (i.e. 10 mg/s Xe).
5. Provision of liquid helium-driven boost pump with up to 400,000 l/s, non-intermittent operation for about 24 hours per week to provide transient best vacuum conditions.

Table 1

Specifications of STG-ET Facility	
General	
Horizontal axis chamber with single door design	
169 mounting ports	
Engine stand with probe holder decoupled from vacuum chamber	
Data	
Length of vacuum chamber	12.2 m
Diameter of vacuum chamber	5 m
Mass of empty vacuum chamber	25 tons
Volume	236 m³
No-load Pressure	$2{\cdot}10^{-6}$mbar (only with turbo pumps)
Evacuation time	2-3 hours (empty chamber)
Engine	
EP Engine Power Range	Up to 25kW input power (current limitation due to target cooling)

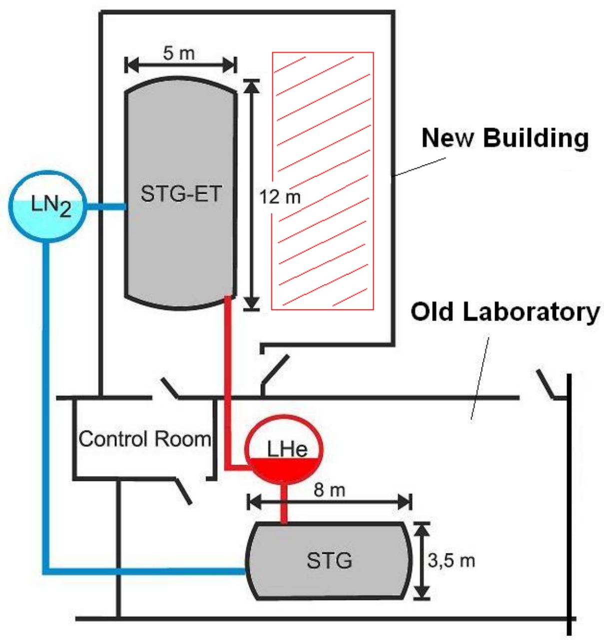

Figure 2: Plan of the STG-ET new building with respect to the existing STG facility with LN2 and LHe supply. The hatched area in the new building shows the space for additional project-specific components to be placed into the STG-ET chamber.

IV. DLR Test Facility STG-ET: Realization

A. General and vacuum chamber

Based on the above considerations, characterizations and requirements the new DLR-facility STG-ET (ET for electric thrusters) was designed and is now being constructed. The maximum nominal input power of engines to be tested in STG-ET is 25kW, which applies to a single engine or to the total power of engine clusters.

To fulfill requirements 1 and 3 a compromise had to be found to match the design of a chamber as large as possible with the available space at the DLR site in Göttingen, and the proximity to the LHe supply (requirement 5).

The design led to a vacuum vessel with a length of 12.2m and a diameter 5m. These dimensions position the new facility within the group of 'very large EP test facilities' [4].

In parallel a new building had been constructed in proximity to the existing STG facility because the large size of the vacuum chamber made this new building necessary. Figure 2 shows a floor plan of the STG-ET new building constructed close to the existing STG facility and the two vacuum chambers. The new building's dimensions are large enough to accommodate exchangeable components on one side of the chamber. The red hatched area in the sketch shows this space for additional project-specific components to be placed into the ET chamber. Both facilities are using the same LN2 and LHe supply.

Figure 3: Assembly of the vacuum chamber segments inside the new building. The chamber segments were assembled in the factory and welded together on site at DLR.

The chamber was built in segments delivered by road transport to DLR and assembled on site. Figure 3 shows how the chamber segments were joined together by welding. By the end of the year 2010 the assembly of the vacuum vessel has been completed. Figure 4 gives an idea of the size of the STG-ET vacuum chamber during commissioning.

Figure 4: View into the empty STG-ET chamber during commissioning (checking of alignment and position of ports and dimensions).

The main data of the chamber are summarized in Table 1. The chamber sits on concrete foundation blocks in sliding bearings so that thermal expansion or changes of shape due to pressure loads minimize undesired deformation. The thruster test stand will be mounted on a separate concrete mounting foundation which is decoupled from the chamber walls. Thus the test stand with thruster and probe holders are supposed not to be affected by movements of or exterior disturbances transferred by the chamber (requirement 2).

B. Pumping System

The pumping system is designed in order to accommodate typical EP thruster mass flows of up to 100 sccm. Specifying the permanent background pressure during operation between about 10^{-6} and 10^{-5} mbar corresponds to an effective pumping speed of 100,000-200,000 l/s for thrusters with mass flow in the order of 10 to 100 sccm Xe (or 1 to 10 mg/s Xe). Based on these values the pumping system was designed with roughing vacuum pumps, turbomolecular pumps, cold heads and liquefied gas cryopumps.

Figure 5 displays a schematic diagram of the vacuum chamber mechanical pumping system. Roughing Pump Stand 1 has a rotating vane and a roots pump with a nominal displacement of 400m³/h for roughing and turbo pump exhaust draining. Pump Stand 2, for roughing and cryopump regeneration, has rotating vane and roots pumps with a nominal displacement of 1950 m³/h.

The estimated regeneration time after 50 operation days at 50 sccm should be of the order of 7h. Pump Stand 2 has the task to quickly evacuate the chamber down to pressures low enough to switch on turbomolecular pumps. These are specified at 2000 l/s pumping speed each. If these are in operation the high flow Pump Stand 2 can be switched off.

The cryopumps consist of seven cold heads, each with 30,000 l/s performance on Xe. They will be mounted behind LN2 baffles and are supposed to operate at temperatures below 42 K. The cryopump system will be completed by a LHe boost pump of 400,000 l/s with a non-intermittent operation of about 24 hours out of the DLR 3000 l LHe tank..

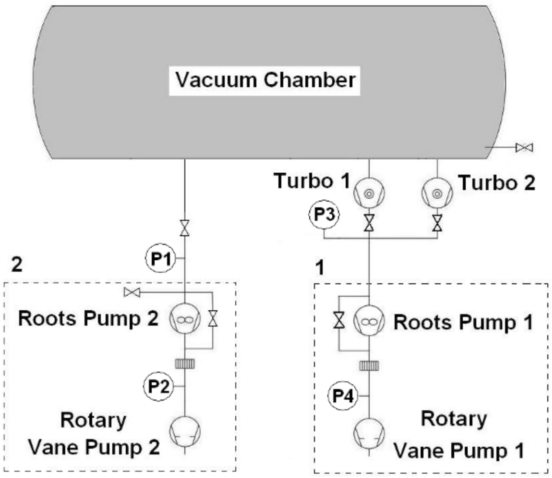

Figure 5: Schematic diagram of the vacuum chamber pumping system comprising two roughing pump stands (1 and 2) and two turbomolecular pumps.

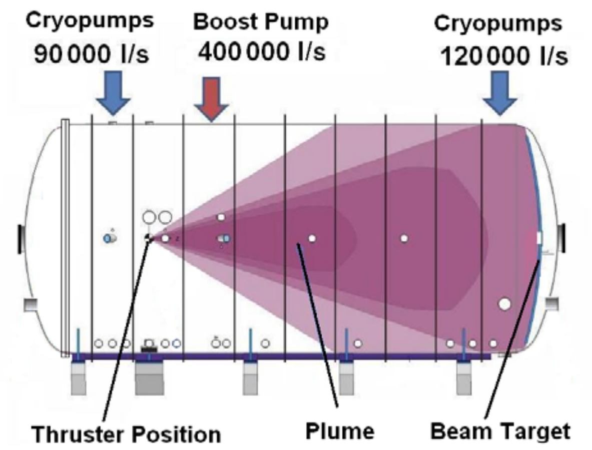

Figure 6: Thruster position in the origin of the chamber coordinate system, cold pumps and plume.

The seven cold heads are being installed at present. The detailed design of the cryo panels, baffles and shrouds will be tackled soon. The liquid helium cryopump will be designed in detail and constructed afterwards. This pump can be operated at temperatures down to about 4.5K and allows evacuation of all gases except helium. Therefore, also novel thrusters with other propellants than xenon, like Kr or Ar, can be tested in this facility too. When switched off the cryopumps can be filled with warm gas (up to about 120°C) in order to speed up the time required for warm-up in case of cryopump regeneration.

Figure 6 shows the thruster position inside the chamber and the planned configuration of cold surface pumping devices in conjunction with the plume geometry. The different cold walls, cryopumps and a beam target are used for dumping the thruster exhaust.

C. Measurement Equipment

The control system and the measurement equipment are still in the design or acquisition phase and the devices listed below are not yet installed. The planning foresees a set of advanced measurement systems for thruster and exhaust plume analysis, in addition to common control sensors.

Figure 7 sketches a schematic diagram of the planned plume diagnostic system. It is based on two ring-shaped holders rotating around the thruster exit equipped with ion current measurement cells. The doubled beam diagnostic shall be able to determine the real thrust vector without assumptions on the beam symmetry and its origin from the centerline of the thruster.

EP beam diagnostic instruments carried by the rings are Faraday cups and Retarding Potential Analyzers (RPA), measuring 0-1100 eV (later up to 2000eV). The instrument measurement ranges are based on typical thrusters like HEMP, SPT, and RIT.

The general experiment monitoring instruments will include a mass spectrometer, neutral particle flow measurement, observation cameras, and a pyrometer for temperature measurement. The data acquisition will record chamber and pump line pressures, will accept thermocouples and RTD's, and parameters of the engine under test (voltage and current, etc.).

An important measurement system is the thrust balance. This device has to accurately measure forces in the mN range with resolution down to several μN. Such specifications must be achieved for masses of thruster plus accessories of the order of 400N or even more. The instrument must be very sensitive and must have electronic noise rejection measures for its sensitive electronics components. Figure 8 gives an idea of the mechanical design of the thrust balance. The scheme is a parallelogram with the advantage that the engine stand plate always stays horizontal [5].

The pillar carrying thruster, balance, and probe holders will be mounted on a concrete block being part of the building foundation. A flexible bellow connects the foundation to the vacuum chamber. In this way the vibrations and movements of the chamber are not transmitted to the engine thrust balance.

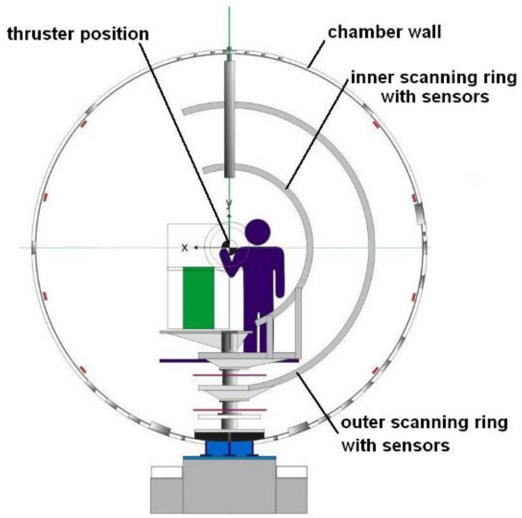

Figure 7: Schematic diagram of the planned plume diagnostic system. It is based on two ring-shaped sensor holders rotating around the thruster exit.

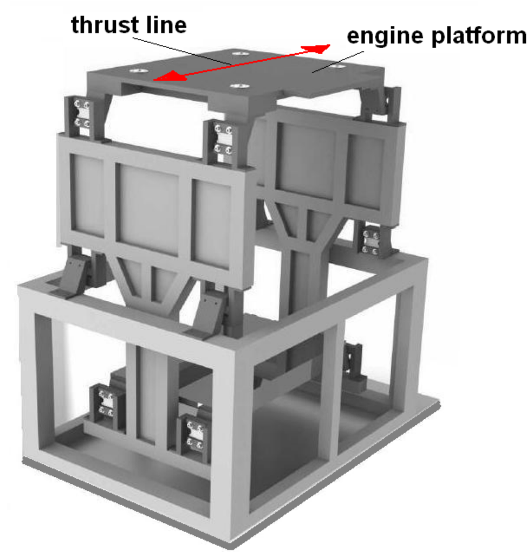

Figure 8: Schematic diagram of the thrust balance an engine platform.

V. First Tests of Chamber

First tests are being conducted in order to get experience in optimizing the pumping and venting procedures, and to test the impact caused by a cold gas thruster on pressure and pressure distribution. The chamber has been equipped with seven pressure gauges which have been compared and crosschecked in a calibration facility prior to their usage in the STG-ET chamber.

Figure 9 shows the pressure decrease during evacuation versus time using one of the two turbopumps. Pump Stand 2 is used first for rough pumping. The correct indication of the pressure gauges starts at 700 mbar. Only the rotating vane pump of Pump Stand 2 ran until time mark 110min. Switch-on of the roots pump gives the kink in the curve. Both pumps ran until time mark 160min, when Pump Stand 1 is switched on. After that the turbopump could be switched on too and Pump Stand 2 has been shut down. The final pressure with one turbomolecular pump settled at $5.5 \cdot 10^{-6}$ mbar after about 3 hours time. Former runs with both turbomolecular pumps reached similar pressures within 2-2.5 hours.

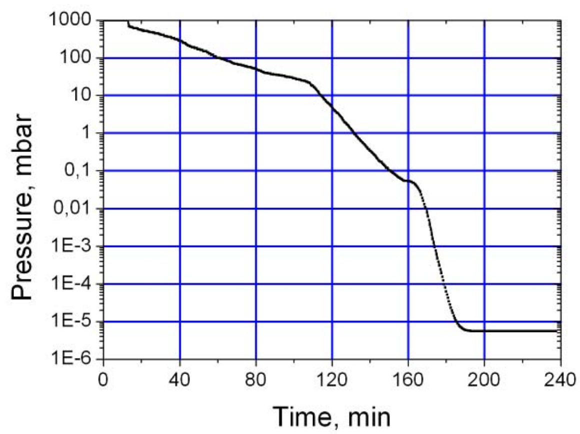

Figure 9: Pressure profile during pump down. It took about 3h to reach $5.5 \cdot 10^{-6}$ mbar.

The initial test with an engine was performed with a cold gas thruster mounted on a pillar at the engine position in the chamber. This test thruster is a device commonly used at DLR Göttingen within chemical thruster investigations. It has a small nozzle and is operated with gaseous nitrogen under pressure. The thruster is mounted on a rotation table so that gas efflux not pointing along the chamber axis can be tested.

Figure 10 shows the pressure change caused by this cold gas thruster flow and the capability of the pumping system. The nozzle throat diameter is 0.6 mm. At the 50s time mark the thruster is switched on and loaded with nitrogen at a stagnation pressure of p_0=50mbar. This leads to a mass flow of 3.24 mg/s and increases the pressure in the vacuum chamber. The actual pump configuration (one turbo molecular pump) is able to reach steady state within a few minutes and runs at about $1.2 \cdot 10^{-3}$ mbar. This long stabilization time is an impressive demonstration of the chamber size.

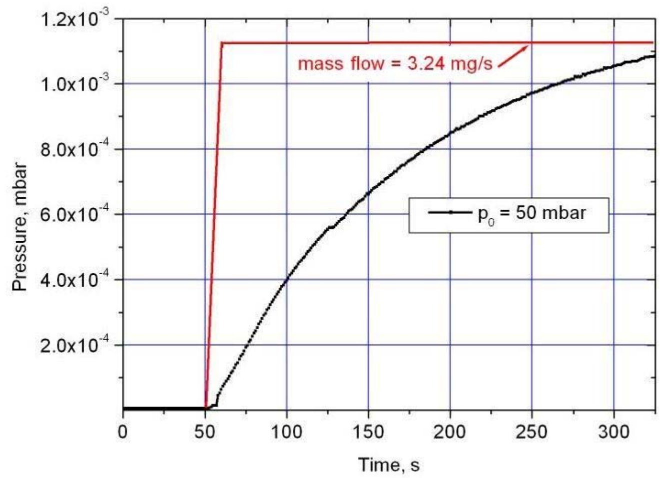

Figure 10: Pressure increase generated by switching on a cold gas thruster (at t=50s). The thruster was loaded with a pressure of 50mbar.

VI. Outlook

The new electric propulsion test facility STG-ET ended its first completion step and commissioning of the chamber. The mechanical pumping system is running and a few tests have been run for checking gas leaks and pump performance. The combination of displacement and turbo pumps, and future cryopumps will give a fast evacuation time and high pumping speed on typical electric propulsion gases.

The chamber with its 12.2m length is the largest vacuum chamber in Germany dedicated especially to EP engine long-term and contamination investigations. The facility started operation mid of 2011 and we expect completion including cold wall pumps in 2012. The new DLR facility and the smaller Jumbo facility in Giessen will be operated within a cooperation agreement between both institutions, including for example EP studies related to chamber size.

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