Overview on Testing Infrastructures and Diagnostic Tools for HEMPT based Ion Propulsion Systems

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In the framework of DLR's HEMPTIS program Thales Electron Devices GmbH (TEDG) develops and qualifies an ion propulsion system based on the High Efficiency Multistage Plasma Thruster HEMPT technology, and produces the respective flight hardware for the SGEO Hispasat AG1 mission. In order to verify the HEMPT system, including its components, versus the mission requirements different testing infrastructures with particular diagnostic tools are used. Short term acceptance and verification test campaigns, performance and thermal vacuum characterization on thruster, thruster module (HTM) and thruster assembly (HTA) level are performed in the ULAN test facility, located at TEDG Ulm. Upgrading is in progress for End-to-End test of Flight Models (FM) on HTM and HTA level. The ULAN includes a large vacuum facility with a volume of 22 m^3 equipped with a combined turbo molecular and a cryogenic pumping system which provides a pumping speed for Xenon of more than 70,000 l/s and a vacuum with the base pressure <10^{-7} mbar. The diagnostic and test support tools include the mass-spectrum analyzer, the energy-selective mass spectrometer, the RPA, the thrust balance, the shroud simulating the cold environment (liquid nitrogen cooling) and the hot environment (electrical heaters), the temperature control of HTM mounting interface. The neutralizer development test facility, located at TEDG Ulm, serves for performance characterization of HCN type cathode-neutralizers. It provides a combined turbo molecular and cryogenic pumped vacuum with a Xenon pumping speed of 10,000 l/s and a base pressure ~10^{-7} mbar. The diagnostic and test support tools include a mass-spectrum analyzer, a pyrometer and a temperature control of the HCN mounting interface. A second neutralizer test facility dedicated to life-time qualification is currently set up. Mechanical tests on the HTM-level are performed at the TEDG mechanical test facility, which involves a vibration desk and which is qualified and utilized for mechanical tests of Traveling Waves Tubes. Some parts of mechanical tests are

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performed at external test facilities at ASTRIUM Friedrichshafen. The endurance and life-time qualification tests on HTM and HTA level are performed at the external test facility at AEROSPAZIO Tecnologie s.r.l., Siena, Italy. It provides a cryogenically pumped vacuum system with a pumping speed for Xenon of 170,000 l/s and the base pressure <3×10^{-8} mbar. The facility allows for a 3D ion beam characterization (Faraday Probes). TEDG has upgraded the facility with own diagnostics tools: a high precision thrust balance and an RPA.

Nomenclature

BOL = Beginning Of Life
DACS = Digital Acquisition System
ET1 = Endurance Test 1
ESMS = Energy-Selective Mass-Spectrometer
FCU = Xenon propellant Flow Control Unit
GSE = Ground Support Equipment
HEMPT = High Efficiency Multistage Plasma Thruster
HEMPTIS = HEMP Thruster In-orbit-verification on SmallGEO
HTM = HEMP Thruster Module
HTA = HEMP Thruster Assembly (HTM + PSCU)
MMS = Mechanical Mounting Structure
NHKS = Neutralizer Heater Keeper Supply
NTR = Neutralizer
PSCU = Power Supply and Control Unit
PRA = Retarding Potential Analyzer
SGEO = Small GEOstationary satellite
TEDG = Thales Electron Devices GmbH
THR = Thruster

I. Introduction

THALES Electron Devices GmbH (TEDG) develops and qualifies an ion propulsion system based on the High Efficiency Multistage Plasma Thruster (HEMPT) technology, and produces the respective flight hardware for the SGEO Hispasat AG1 mission. The HEMPT Ion Propulsion System, referred to as HEMP Thruster Assembly (HTA), consists of a Power Supply and Control Unit (PSCU) and four HEMPT Modules (HTMs). Each HTM integrates a HEMPT, a hollow cathode neutraliser HCN and a propellant flow control unit (FCU) [1,2,3]. In order to verify the HEMPT System including its components versus the mission requirements different testing infrastructures with particular diagnostic tools are used.

TEDG makes use of three vacuum test facilities when the flight-representative conditions in terms of ambient pressure are required. These are:

- ULAN vacuum test facility at TEDG Ulm, for short-term acceptance and verification test campaigns on thruster, HTM and HTA level; these test campaigns include perfromance and thermal vacuum characterization;
- Neutralizer vacuum test facility at TEDG, Ulm, for performance characterization of HCN-type cathode-neutralizer;
- LVTF1 vacuum test facility at Aerospazio Siena, Italy, for endurance and life-time qualification tests on HTM and HTA level.

TEDG performs mechanical tests at the following facilities:

- Mechanical test facility at TEDG ULM for vibration tests;
- Mechanical test facilities at ASTRIUM Friedrichshafen and CASSIDIAN Ulm

II. ULAN vacuum test facility

The ULAN vacuum test facility was built up in 2005 (ULAN stands for “Ulmer Anlage” in German language, “Ulm’s facility”) to improve the test capabilities of HEMP development project [4]. Since that the ULAN (Fig. 1) has been progressively upgraded till a complex facility providing the complete infrastructure for testing of several thrusters or HTMs, and offering multiple types of characterization on the thruster, HTM and HTA level, such as:

- thruster full performance characterization (thrust and electrical parameters, time-averaged and nonstationary);
- plume diagnostics in terms of angular distributions of ion current density, ion energy, ion charge state;
- thermal-vacuum characterization;
- compatibility test with the flight representative hardware.

ULAN has recently accomplished the HTM-EM3 acceptance tests before the Endurance 1 test[5], the HTM-EM4 performance and thermal vacuum tests[2], coupling tests with the PSCU. Presently, the HTM-EM3 post-endurance test is going on[5].

A. Vacuum chamber

The vacuum chamber has 2.4 m in diameter and 4.0 m in length, with an effective internal volume of 22 m^3. Both ends are closed with motorized doors allowing the access into the chamber (see Fig. 1). The internal chamber walls are presently coated with aluminium for more stable thruster performance[5]. The chamber walls can be heated for accelerated outgasing and theerfore for achievement of betetr vacuum conditions. The chamber walls can be also cooled down allowing for the operation of thrusters or thruster clusters up to 40 kW total beam power.

The ULAN pumping system includes three stages:

- rough pumping system till <1 mbar;
- two 2000 l/s turbo-molecular pumps (backed by the rough pumping system) able to reach $<10^{-5}$ mbar; for non condensing gases like hydrogen and helium;
- cryogenic pumping system consisting of 8 cryoheads with plates immersed into the chamber providing an effective xenon pumping speed of more than 70000 l/s.

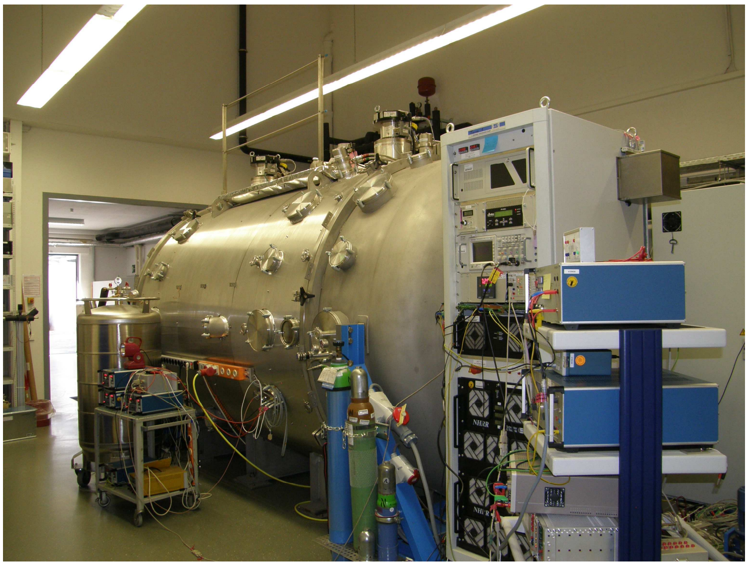

Figure 1. ULAN test facility.

The vacuum conditions are continuously monitored by three vacuum gauges, one installed 3 m downstream the thruster, second behind the thruster, third at the thruster exit plane. The residual gas composition is constantly monitored with a compact mass-spectrometer. The ultimate base pressure reached after bake-out of the chamber walls is in the low 10^{-8} mbar. Typical Xe pressure during the HTM testing is 4×10^{-6} mbar. For reaching the atmospheric pressure after test the chamber is flooded with dry nitrogen to keep water vapor adsorption to the walls as low as possible.

B. In-vacuum test set-up and diagnostic tools

The vacuum chamber is permanently equipped with a thrust balance (TEDG development[4]), installed on the rotating table. The thrust balance has a basic design of a parallelogram made out of stiff girders supporting a table. The joints between girders and table are flexible so that the girders form a double pendulum. The thrust measurement accuracy is ±0.2 mN. The thruster or HTM is positioned inside the chamber on top of the thrust balance (Fig. 2). The thruster axis coincides with symmetry axis of the cylindrical vacuum chamber. The distance between the thruster exit and the bottom of the chamber is 3.5 m. All electrical cables and a gas line to HTM, mechanical interface cooling lines are routed through the thrust balance in such a way to avoid the influence of their distortion on thrust measurements.

The RPA (TEDG development[4,6]) is installed on the boom in front of the thruster, slightly off-axis (Fig. 2). Two types of RPA are currently used: a gridded RPA[4] and a single orifice RPA[6], which has unique capabilities of very low acceptance angle. The distance between the RPA and the thruster exit is set to 1 m, but can be reduced or increased till max 3.5 m according to test specifications. The RPA position is laser-adjusted relative the thruster in such a way, that the RPA symmetry axis and the thruster axis were in the same horizontal plane and they intersected in the point of the thruster exit plane. In this configuration, the thruster is rotated around the vertical axis in the thruster exit plane. The RPA is used for obtaining the ion current density and ion potential angular distribution.

The energy-selective mass-spectrometer (ESMS) is installed on the downstream door of the vacuum chamber, on the chamber axis. ESMS is utilized for obtaining the ion energy and ion charge state angular distribution[6].

The main parameters of TEDG RPA and ESMS are presented in Table 1.

	Gridded RPA	Orifice RPA	ESMS
Ion energy range	0..2000 V	0..2000 V	0..2000 V
Entrance orifice	∅20 mm (multiple holes of ∅0.3 mm)	∅1 mm (single hole)	∅1 mm (single hole)
Detectable ion charge states	no	no	till Xe^{5+}

Table 1. RPA and ESMS parameters at ULAN test facility.

The thermal vacuum characterization of HTM is performed with the use of thermal shroud (Fig. 3). Thermal shroud simulates the extreme in-flight background temperatures, which are:

- no sun (T_{space} = -200°C) simulated with LN2 cooling (T_{Shroud} = -170 ± 10°C)
- worst-case sun direction (T_{space} = +100°C for THR radiators) simulated with electrical heaters located on the thermal shroud (T_{Shroud} = +100 ± 5°C);

The thruster and neutralizer protrude from the hole in the frontal copper plate of the shroud. The shroud encompasses the thruster radiators completely (the radiators are visible on Fig. 2). The shroud is feed with liquid nitrogen from the Dewar vessel through the dedicated lines equipped with an “on-off” valve (a 300 l Dewar is visible in Fig. 1).

The shroud performs an additional function of protecting the HTM from the chamber wall sputtered material during the thruster operation. Therefore, the shroud is always installed with HTMs during all tests of EM and in the future of QM and FM models. In this case the shroud is feed with cooling water from the general facility circuit and is kept at constant temperature of +20°C±3°C.

ULAN provides the capabilities of thermal stabilization for in-vacuum devices. The HTM mechanical interface (mounting flange on the thrust balance) can be continuously kept at any temperature between -15°C and +80°C. This is achieved by using of cryomats with liquid working body installed outside the vacuum chamber.

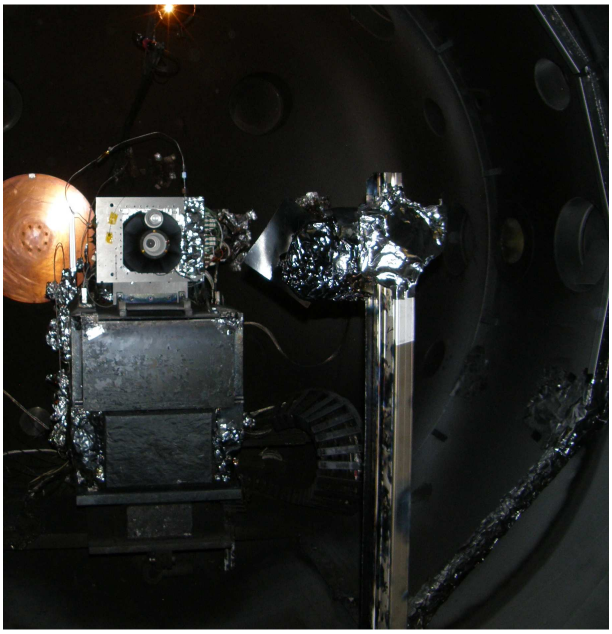

Figure 2. Position of HTM on top of the thrust balance during the test at ULAN facility; the RPA is seen in front plane.

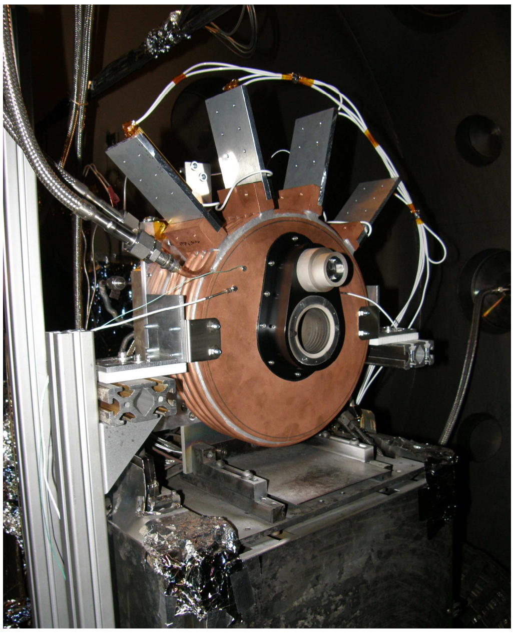

Figure 3. HTM with the thermal shroud at ULAN facility.

C. Electrical set-up, gas system and GSE

ULAN facility allows for operation of the thruster, the cathode-neutralizer and the FCU from the laboratory power supply as well as from the flight-type PSCU.

The electrical set-up and data-flow diagram for operation from the laboratory power supplies is shown in Fig. 4. The thruster discharge is powered with a 10 kW, 2000V dc anode power supply (PS1), which has an interlock entrance. The return line of anode power supply (negative pole) is connected to the electric propulsion (EP) ground. The anode power supply can operate in floating configuration (EP-ground floating) and in grounded configuration (EP-ground is connected to the facility ground). The heater of cathode-neutralizer is powered with a 15V, 5A AC power supply (PS3). The keeper discharge of cathode-neutralizer is powered with a 50V, 4A DC power supply (PS2), which has an interlock entrance. The facility has separate power supply units of 24V dc, 15V dc, 12V dc, 5V dc to power the FCU, the thrust balance, the interlock electronics, measurement sensors.

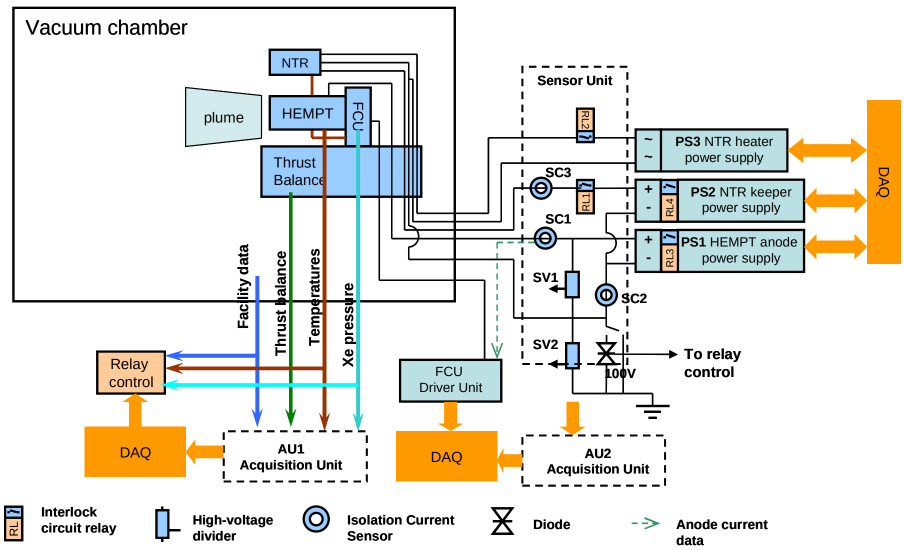

Figure 4. ULAN electrical test set-up.
PS – power supply; SC – current sensor; SV – voltage sensor (high-voltage divider), AU –acquisition unit.

The protective relays are commanded from the interlock circuit, which monitors the vacuum level, thruster temperatures, Xe supply pressure.

Electrical connections inside the vacuum chamber are performed with cables having PTFE isolation. Lemo connectors and feed-throughs, as well as SubD connectors and feed-throughs are used to pass the electrical lines into the vacuum chamber.

ULAN provides a complete set of GSE for operation of PSCU, including the satellite bus simulator, the PSCU commanding interface (MIL-1553), the PSCU thermally stabilized mechanical interface.

Transient behavior of electrical parameters is observed on the oscilloscope via dedicated voltage or current probes.

The gas supply system is fed with Xe at 2..4 bar from a 10 liters Xe-bottle through the pressure reducer. The gas flow is measured and/or controlled by the gas flow meters and by digital pressure controller, which are installed outside the vacuum chamber at no more than 2 m from the gas feedthroughs. Pressure sensors monitor the Xe line pressure outside and inside the vacuum chamber. Xenon 4.0 purity grade is used. The gas system has free ports for connection of flight-type gas equipment, e.g. a satellite gas managing system.

The connection inside the vacuum chamber from the feed-through to thrust balance is made from the PTFE tube, all other pipings are from stainless steel tubes with Swagelok 1/8” and VCR 1/4" connections.

All equipment is controlled from the digital acquisition system DACS. All electrical parameters are delivered from the measurement devices to the DACS. All power supplies, mass-flow and pressure controllers are commanded via digital or analogue interfaces directly from the DACS computer. The power supplies deliver the output voltage, current, status information to the DACS. The main functionalities of all equipment are accessible via an interface program.

III. LVTF1 vacuum test facility at Aerospazio

The LVTF-1 vacuum test facility at Aerospazio, Siena, Italy, was built up in earlier 2000s for the purpose of electric propulsion testing. It provides an excellent long-term vacuum stability, and a unique 3D beam current diagnostics. All this makes the LVTF1 suitable for long term testing of HEMP thrusters and HTMs. LVTF1 has recently accomplished the 1200h HEMP Shakedown test (2009) and the 4000h HEMP HTM-EM3 Endurance test.

A. Vacuum chamber

The LVTF-1 consists of a diamagnetic horizontal stainless steel cylinder with two full-diameter end caps, which can be removed to allow the introduction of large test articles (Fig. 5). The chamber is 11.5 m long and has a diameter of 3.8 m for a total volume of ~120 m3. On the side of the chamber there is a number of flanges (up to three 900 mm diameter large flanges) which allow connecting additional service chambers.

For HEMP testing, the usable test volume consists of a cylinder of about 3.7 m diameter (with graphite protective shields installed) and ~7 m length. A water-cooled chevron beam target is mounted at the chamber end opposite to the cryogenic system. The target is covered with pure graphite plates to minimize sputtering toward the thruster. The interior of the test facility is also fully lined with pure graphite panels.

Figure 5. The LVTF-1 facility at AEROSPAZIO.

The pumping system includes:

- 1st stage consisting of rotary pumps operated in parallel during the first phase of the pump-down (1Bar ÷ 10 mbar);
- a 2nd stage consisting of one Roots pump backed by a rotary pump (10 mbar ÷ 4E-02 mbar);
- a 3rd stage consisting of two turbo molecular pumps backed by Rotary pumps (4E-02 mbar ÷4E-05 mbar) able of providing more than 2.000 l/s pumping speed in overall;
- a 4th stage consisting of a commercial cryogenic pump;
- a 5th stage consisting of a special system of six panels cryogenically cooled by cold heads and surrounded by liquid nitrogen baffles, specifically designed to pump Xenon (pumping speed >170.000 l/s for this specific test).

The minimum attainable basis pressure on the order of 2×10^{-8} mbar, typical Xe pressure during HTM testing is 2.2×10-6 mbar.

The vacuum level is monitored with the help of 3 full-range Leybold Ionivac ITR90 gauges. They are mounted behind manual gate valve in order to allow their substitution for recalibration-maintenance without break of vacuum operations. The vacuum quality (residual gas analysis) is monitored with a Quadrupole Mass Spectrometer QMS (200 a.m.u.) throughout the test campaign.

LVTF-1 has a chamber conditioning system in order to properly outgas the inner surfaces of the chamber during the pump-down phase. It consists of a high power fixed mounted heater.

Presently, the LVTF1 is being modified for accommodation of two HTM simultaneously, of two thermal shrouds and one PSCU.

B. In-vacuum test set-up and diagnostic tools

The vacuum chamber is equipped with a thrust balance (TEDG development[4]). The HTM is placed on top of the thrust balance in such a way as to be positioned in Thruster Station 1 (Fig. 6).

The thrust balance is a further development of the ULAN thrust balance, with a better thermal stabilization. It has a very low thermal drift. The main parameters of the thrust balance are presented in Table 2:

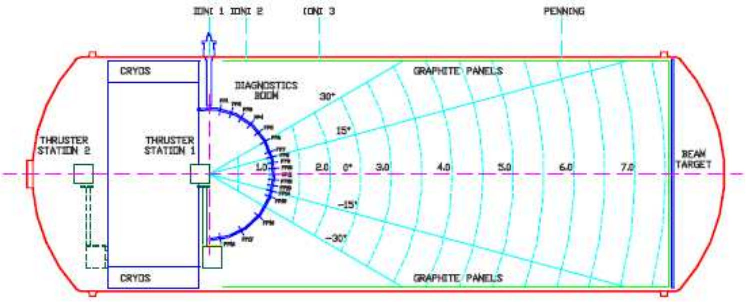

Figure 6. Vacuum set-up in the Aerospazio test facility (side view).

Thrust range	0 – 500 mN
Accuracy	±0.1 mN
Reproducibility	<0.05 mN
Thermal drift	<1 mN / K under vacuum conditions

Table 2. TEDG Thrust balance characteristics.

The ion beam diagnostics set is mounted on a rotating semicircular arm inside the chamber and consists of

- 32 Faraday Probes (FP) with guard ring placed at different angular positions on the arm which is used to determine the thrust vector (via ion current measurements);
- 1 RPA provided by TEDG, with the same characteristics as for ULAN facility (see Table 1).

The thrust balance is equipped with an adjustment mechanism allowing for positioning and orientation of the HTM with respect to the beam diagnostics according to the following criteria (see Fig. 7):

1) the vertical rotation axis of the beam diagnostics arm should be situated in the thruster exit plane;
2) the vertical rotation axis of the beam diagnostics arm should intersect the thruster symmetry axis;
3) the centre of the thruster exit plane (intersection point of the diagnostics rotation axis and the thruster symmetry axis) should coincide with the centre of the semicircular rotating arm.

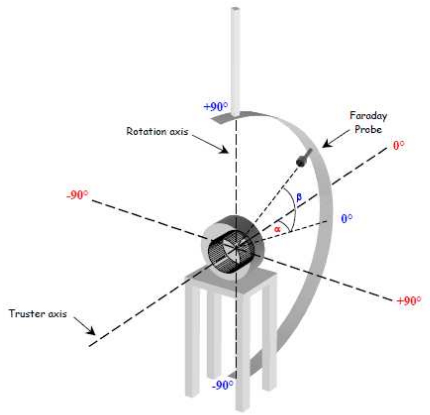

Figure 7. Definition of generalized coordinates for the thruster diagnostics reference system at LVTF1.

Each probe is mounted on the arm so that the collector faces the centre of thruster exit section at a distance of 1 m. The position of a probe w.r.t. the centre of the thruster is determined by α and β angles, where α is the angular position of the arm w.r.t. thruster axis and β is the angular position of the probe on the arm, as shown in Figure 6. This configuration enables complete 1m-radius hemispherical profiles of the exhaust plume to be obtained.

The arm is moved by a stepper motor with a step angle of 0.45 deg and can perform a 180 deg rotation (-90 deg to +90 deg off axis). The arm is equipped with an absolute encoder. The angular position of the probes can be accurately set +/-0.5 deg, the radial distance inaccuracy is about 0.1%. The angular accuracy of the probes is also influenced by the thermal deformations which can occur on the rotating boom when it stays at rest close to the cryogenic system, as well as the oscillations of the boom especially at the start of the movement.

C. Electrical set-up, gas system and GSE

Power supplies and electrical circuit of the test bench are fully provided by TEDG. The current configuration is for HTM operation from laboratory power supplies. All power supplies, interlocks and measurement units are installed into a standard 19” rack. The rack supplies the thruster, the cathode and the FCU with electrical power and acquires information from the remote sensors. The electrical set-up and data-flow diagram is the same as for ULAN test facility (see Fig. 4).

Electrical connections inside the vacuum chamber are performed with cables having PTFE isolation. Lemo connectors and feed-throughs are used to pass the electrical lines into the vacuum chamber.

All equipment is controlled from the DACS. All electrical parameters are delivered from the measurement devices to the DACS.

The Xe supply system is provided completely by TEDG. It has 10 Xe-bottles of 10 liters each installed into two banks. Each bank has own gas filter, pressure reducer, pressure sensors, pneumatic valves for remote bank switching. The laboratory FCU of Xe supply system is designed to provide two HTMs with Xenon; it is installed outside the vacuum chamber at no more than 2 m from the gas feed-throughs. The operational gas-flow controller pressure is fine-regulated with the digital pressure regulator. The gas flow is measured by the gas flow meter and can be regulated by the gas-flow controller. Several connections are foreseen for line-purging. On the vacuum-side gas line, a pressure sensor is installed immediately before the HTM.

All pipes inside the vacuum chamber as well as outside consist of stainless steel tubes with Swagelok 1/8” and VCR 1/4" connections.

All mass-flow controllers and pressure regulators are remotely controlled via serial interface. The pressure sensors deliver a signal to the DACS.

The HTM operation at all stages is remotely controlled from Ulm by TEDG via TCP/IP connection.

The electrical circuit is currently under modification to accommodate the GSE for PSCU operation.

IV. Neutralizer vacuum test facility

The neutralizer vacuum test facility served for development of HCN5000 type[3] cathode-neutralizers. It is mainly used now for qualification of HCN5000 cathodes.

The vacuum chamber of the neutralizer test facility has a diameter of 0.4 m and a length of 1 m (Fig. 7). The chamber walls can be heated for accelerated outgasing and therefore for achievement of better vacuum conditions. The pumping system includes three stages:

- rough pumping system till <10 mbar;
- one 560 l/s turbo-molecular pumps (backed by the rough pumping system) able to reach ~10^{-6} mbar; for non condensing gases like hydrogen and helium;
- cryogenic pumping system consisting of 1 cryohead immersed into the chamber providing an effective xenon pumping speed of more than 10000 l/s.

The vacuum conditions are continuously monitored by vacuum gauges. The residual gas composition is constantly monitored with a compact mass-spectrometer. The ultimate base pressure reached after bake-out of the chamber walls is ~1×10^{-7} mbar. For reaching the atmospheric pressure after test the chamber is flooded with dry nitrogen to keep water vapor adsorption to the walls as low as possible.

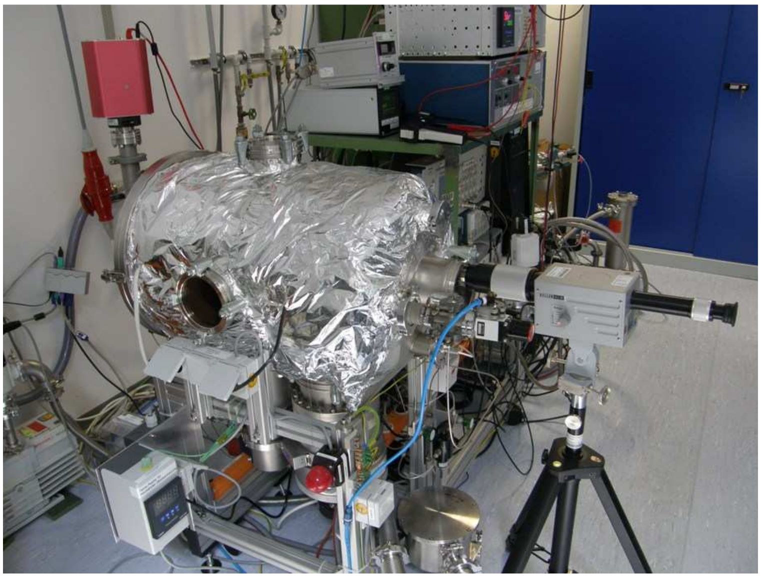

Figure 8. Neutralizer test facility at TEDG in Ulm.

The cathode-neutralizer is installed horizontally so that its axis coincides with the chamber axis.

The chamber is equipped with several view ports, one of them on the chamber axis is used for the pyrometer, installed outside the vacuum chamber. The pyrometer allows for measurement of cathode emissive element temepetrature, where the contact temperature measurement methods are impossible.

The most frequently used electrical configuration is that where the cathode floats relatively the chamber, the chamber walls serving as anode for the emitted electron flow. The heater of cathode-neutralizer is powered with a 15V, 5A AC power supply. The keeper discharge of cathode-neutralizer is powered with a 30V, 3A DC power supply. The electron emission current towards the chamber walls is extracted with a 30V, 3A DC power supply. The facility has separate power supply units of 24V dc, 15V dc, 12V dc, 5V dc the interlock electronics and measurement sensors.

The protective relays are commanded from the interlock circuit, which monitors the vacuum level, Xe supply pressure.

The Xenon supply system is fed with xenon at 2..4 bar from a Xe-bottle of 10 litres, through the pressure reducer. The gas flow controller is installed outside the vacuum chamber at no more than 1 m from the gas feed-through. A connection is foreseen for line-purging. The line gas pressure is measured with the pressure transducer. The operational gas pressure inside the cathode-neutralizer is fine-regulated with the gas flow controller. An Oxygen absorber can be installed outside the vacuum chamber for additional purification of the xenon. All piping is from stainless steel tubes with Swagelok 1/8” connections.

A second neutralizer test facility is under set-up, with a similar pumping system; it will be dedicated for long-term test of cathode-neutralizers.

V. Mechanical test facilities

The vibration test on component and HTM level are performed at TEDG vibration test facility, which is qualified for mechanical tests of Traveling Wave Tubes (Table 3).

Generated force, continuous rating	57.8 kN (peak, sine) 55.6 kN (random, rms)
Armature assembly effective weight	45.4 kg
Maximum free table acceleration	1275 m/s^2
Maximum velocity	1.8 m/s
Shaker stroke	51 mm pk-pk

Table 3. Key figures of vibration test facility atTEDG.

The shock test on component and HTM level are performed at EADS-Astrium shock test facility located in Friedrichshafen, Germany. The shock test facility is optimized to simulate the mechanical shocks which may occur during transport, launch and deployment events especially with Ariane 5 spectrum (Table 4). The shock pulse is generated by a falling mass on a ringing plate.

Frequency Range	100 Hz – 10 kHz Typical Ariane 5 Separation
Acceleration (Shock Response Spec.)	Shock Spectrum up to 3.000 g Frequency Range 2 to 10 kHz max. Box Mass 15 kg
High Acceleration Mode (up to 10.000g)	Frequency Range 6 – 8 kHz max. Box Mass 2 kg

Table 4. Key figures of shock test facility at EADS-Astrium in Friedrichshafen, Germany.

VI. Conclusion

Thales Electron Devices GmbH TEDG has a several facilities covering the major part of testing activities on the component, HTM and HTA level. A variety of diagnostic tools allows for full characterization of HEMP thruster, HTM and HTA, and thus allows for verification of requirements in the frames of SGEO Hispasat AG1 mission. Specific tests, such as long-term qualification and lifetime test of HTM and HTA, shock tests are performed at external facilities, where the test infrastructure is upgraded with the TEDG developed equipment.

Acknowledgments

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