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Semi-anechoic chamber for electromagnetic compatibility tests of electric propulsion thrusters

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Abstract

The present work deals with electromagnetic compatibility (EMC) investigations in the field of electric propulsion (EP). A semi-anechoic chamber (SAC) was set up to perform EMC tests with thrusters under operating conditions. The facility includes a semi-anechoic room and a vacuum tank. The measurement electronics currently have an upper frequency limit at 18 GHz. Initial measurements were done operating a Pulsed Plasma Thruster (PPT) to familiarize with the electronic systems. The same device under test (DUT) was investigated in a reverberation chamber (RVC) to obtain comparative results which showed good agreement. Furthermore, the anechoic chamber shows satisfactory initial measurement characteristics, which will be further tested and improved in the future. Characteristics such as chamber pressure, base noise show realistic values. The next steps are to perform measurements on radio-frequency ion thrusters (RIT) including peripherals and cabling.

Keywords: Electric propulsion, Electromagnetic compatibility, Semi-anechoic chamber, Radiation

Introduction

Nowadays, electric thrusters are important propulsion systems in space. Increasing commercialization has a major impact on space flight and especially on electric propulsion. Strong reasons for emerging space travel are scientific, political, military and economic objectives. The still existing challenges are leading to extensive research in energy efficiency, electromagnetic compatibility, alternative propellants, and scalability, to name a few [1]. Electromagnetic compatibility is “the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment”, as defined in [2]. EMC technology for spacecraft is based on traditional theory, but the situation is further complicated by requirements on weight, reliability, space environment, and cost. For this reasons, the commonly used ferrite absorbers or an additional shielding may not be the first choice. Therefore, design methods should focus on bonding, grounding, routing and cable layout. Since spacecraft are typically subject to various operating conditions, e.g., integration testing, launch, and on-orbit operation, special attention should

be paid to the effects of these conditions on the electromagnetic environment (EME). Hence, the EMC characteristics of the spacecraft are associated to its EME [3]. To meet these requirements, a vacuum EMC test facility is used. In past studies some parts of the thruster assembly have been studied separately, e.g., a radio-frequency generator was investigated for its EMC by simulation and measurement. It became clear that the supply lines and the cabling to the thruster are the decisive influencing factors from an EMC point of view [4]. Furthermore, a honeycomb was designed in a previous research work. This is located in the vacuum tank and ensures the absorption of electromagnetic interference from outside [5]. With these basics, the holistic view of the assembly will now be carried out with the help of the SAC.

The latest searches show that there are only a few such facilities in the world. Moreover, the facility considered here is the only one in the university environment. Another test facility is located in California at the company “The Aerospace Corporation”. The basic design is the same as the one presented here [6]. The “Research Institute of Applied Mechanics and Electrodynamics of the Moscow Aviation Institute (RIAME MAI)” also has an identical facility [7]. Zhang et al. also describe an EMC test facility. There is no indication of where this facility is located [3]. The design of the facilities presented is consistent with the design of this facility. The honeycomb chimney is a proprietary development that is not used elsewhere. However, this setup is crucial because it ensures trouble-free operation of the vacuum chamber. The honeycomb chimney is gas-permeable but EMC-tight.

The device under test is a pulsed plasma thruster. The PPT was designed by the Institute of Space Systems (IRS) at the University of Stuttgart for the CubeSat GreenCube and is called PETRUS 1J. The propulsion module contains a group of four PETRUS pulsed plasma thrusters with a common 1 joule capacitor bank. As a fully integrated system, this DUT does not require a complex external power supply system, apart from a voltage source and two communication cables. The charging voltage of the capacitor bank is 5 volts [8].

The main goal of the ongoing research is the completion of the vacuum EMC chamber and the proper operation of the measurement equipment. Furthermore, the matches of the reverberation chamber and absorber chamber are to be worked out. Possible differences are to be explained. The radiation characteristics of the PPT are to be verified, both chambers are necessary for this purpose.

The motivation of this work is presented in Section [Motivation](#). Section [Facility design](#) describes the structure and components of the test facility. Additional features are shown in Section [Facility features](#). Section [Comparison: Reverberation chamber](#) compares the test facility with another facility using a different physical principle. Initial measurements are shown in Section [Measurement](#), including various operating points of the thruster. Finally, in Section [Conclusion](#), a summary of the work and its outputs is given, along with an outlook.

Motivation

Ion thrusters, which constitute an essential part of “NewSpace” missions, play a major role in spacecraft systems for propulsion and maneuvering. Therefore, the thrusters and their peripherals must be safe and reliable. In addition to functionality, electromagnetic

compatibility requirements must also be met to always ensure stable operation under all operating conditions. Furthermore, the mutual interference of active high-frequency components - such as the radio-frequency generator typically used with RF ion thrusters - and satellite components regarding immunity and emissions must be considered. In fact, the electronics constitute about 60 % of the total thruster assembly, which shows the importance of examinations of those allegedly “peripheral” components and their interaction with the thruster itself and other satellite components.

Facility design

The vacuum EMC test facility consists of two parts. Figure 1 shows a schematic representation. The first part, a semi-anechoic chamber, describes a defined environment for EMC testing. In general, it is a room consisting of a metallic, electrically conductive housing in which EM fields are decoupled from the outside. In addition, the walls and ceiling are covered with absorber material to eliminate reflections and thus mimic far field conditions. There are two panels in the floor to connect the DUT to all necessary cabling and further supply lines from the outside. There are also two panels in the wall to supply the anechoic room with gas for the thruster and water for cooling systems. Another important aperture is the feedthrough to the vacuum vessel. It is made with a GRP (glass-fibre reinforced plastic) cylinder with an epoxy resin. The wall thickness is about 21 mm. On both sides of the wall is still a UV protective layer. A metal flange connects the GRP cylinder and vacuum tank. The material has the advantage of being transparent to electromagnetic radiation to a certain extent. The transparency function as well as the influence of the metal flange are subject to an ongoing investigation. This characteristic allows to perform radiation and susceptibility measurements. The vacuum vessel is shown in Fig. 2. It contains a beam dump, a honey comb and several openings for pumps, feedthroughs and sensors. The honey comb was previously researched and laid out as described in [5]. Simulations resulted in a damping of the radiation with more than 100 dB using long honey comb chimneys. The pumping system consists of a backing pump, a turbomolecular pump and a cryopanel which are located adjacent to the tank. The backing pump is a “Leybold DRYVAC DV 200” with a nominal pumping speed of 210 m³/h and an ultimate pressure of 0.01 mbar. The turbomolecular pump is

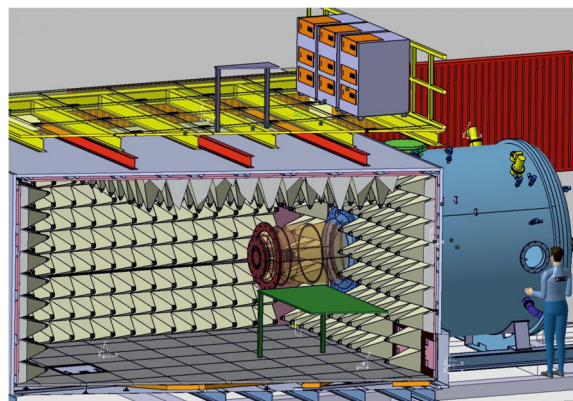


Fig. 1 Conceptual drawing of the vacuum EMC test facility: Semi-anechoic room (left) and vacuum vessel (right)

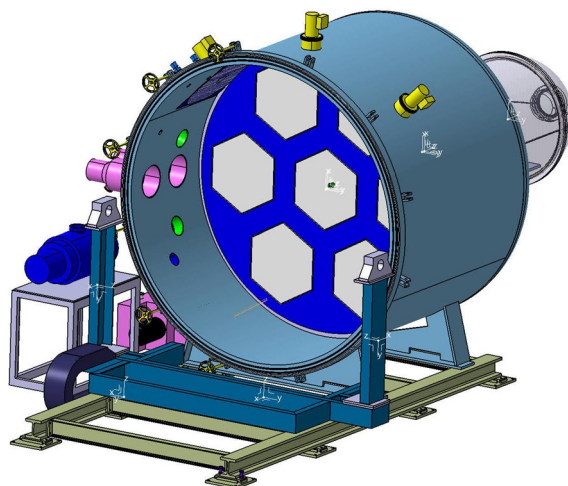


Fig. 2 Conceptual drawing of vacuum vessel: GRP cylinder, beam dump and honey comb

a “Edwards STP-iXA4506C” with a rated speed of 24200 rpm or 30001/s. The thruster is mounted inside the GRP cylinder. A beam dump is used to absorb particle energy. Behind it is a honey comb that ensures that the vacuum area of the facility is completely free of radiation from the outside, caused by vacuum pumps, gauges and other feedthroughs. Thus, the entire pumping system is located in an EMC-tight but gas-permeable second part of the vacuum vessel. A general measurement setup includes a DUT, an antenna and measurement electronics. The DUT consists of a thruster and its peripheral devices, e.g. in case of a RIT: a radio-frequency generator and high voltage power supplies for the grids. The measurement electronics include the signal generators and amplifiers for susceptibility tests and analyzers for radiation testing.

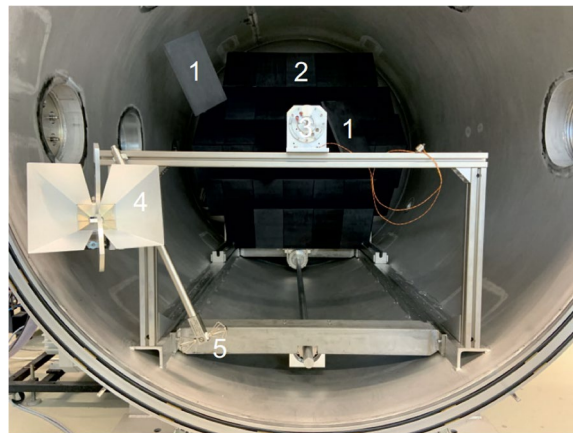
The measurement electronics is formed by Rohde & Schwarz systems. The measuring procedure is controlled and evaluated by the software EMC32 version 11.40.00. The signal generator is a “Rohde & Schwarz SMB 100A” with a frequency range of 100 kHz to 20 GHz. The hardware control unit is a “Rohde & Schwarz OSP220” model, this is used to switch various signal paths on or off, depending on the hardware configuration and test setup. The spectrum analyzer is a “Rohde & Schwarz ESW26” with a frequency range up to 26.5 GHz. The used antenna is a “Schwarzbeck VULB 9162” with a frequency range of 25 MHz to 8 GHz.

Facility features

The anechoic room is 5.5 m long and 4.8 m wide. The height is about 3.2 m. It is designed for a frequency range from 30 MHz to 40 GHz. Emission and immunity tests comply with MIL and ECSS standards. The standard distance between the antenna and DUT is specified as 1 m. The vacuum vessel has a diameter of 2.75 m. The current configuration of the electronic equipment is divided into emission and susceptibility tests. Furthermore, a distinction is made between conducted and radiated investigations. Thus, there are four testing conditions: conducted emissions (CE), radiated emissions (RE), conducted susceptibility (CS) and radiated susceptibility (RS). The following Table 1

Table 1 EMC measurement options and ranges

CE (differential-mode)	30 Hz to 100 MHz
CE (common-mode)	100 kHz to 100 MHz
RE (low frequency)	electric and magnetic field
RE (electric field)	30 MHz to 18 GHz
CS (differential-mode)	30 Hz to 100 kHz
CS (common-mode)	50 kHz to 100 MHz
RS (magnetic field)	30 Hz to 100 kHz
RS (electric field)	30 MHz to 18 GHz

**Fig. 3** Reverberation chamber at Justus-Liebig-University: (1) mode stirrer, (2) beam dump, (3) thruster, (4) and (5) measurement antennas

shows the frequency ranges for each measurement option. Currently, the limitation in frequency is 18 GHz. An upgrade from 18 GHz to 40 GHz is planned.

There are also some limitations, which are issues in an ongoing research, that must be considered when using thrusters. The size of the thruster under investigation depends on the divergence angle of the ion beam, due to the nature of the vacuum vessel. Finally, the ion beam should not hit the walls of the tank, but the beam dump. Initial approaches indicate that a size of RIT-10 to RIT-15 from the manufacturer ArianeGroup is possible. For more information about the RIT properties, see [1]. Furthermore, it will be investigated whether CubeSat systems can also be completely measured. Another influence is the limitation by thermal management, especially for endurance tests. Due to the pumping speed of the pumps, a gas flow of 50 sccm should be possible.

Comparison: Reverberation chamber

Another facility for diagnosing EMC characteristics is a reverberation chamber (see Fig. 3), which is also operated at Justus-Liebig-University in Giessen. The chamber is 1.6 m in diameter and approximately 2.4 m long. The dedicated pumping system consists of two backing pumps and a turbomolecular pump and reaches an initial pressure of less than 10^{-6} mbar, which increases to about $3 \cdot 10^{-6}$ mbar when $q = 0.25$ sccm Xe propellant flows into the chamber. The laboratory is air-conditioned to minimize the temperature effects on the equipment and the feed system. The vacuum chamber has a graphite

beam dump, which collects the ejected ion plume [9]. The purpose of this concept is to investigate the applicability of a reverberation vacuum chamber in the field of electric propulsion. The DUT and other peripherals to be investigated are operated in the chamber. The RVC is based on the principle of a cavity resonator, where usually only discrete modes propagate, which means that discrete frequencies can be observed at high field strength, while medium frequencies are strongly attenuated. To obtain a continuous frequency spectrum, at least one rotating metal stirrer is used, which changes the EM boundary conditions depending on its angular position. A time-varying mode spectrum is measured with the introduced measurement equipment and an antenna with a frequency range from 500 MHz to 18 GHz. Measurements in the reverberation chamber are possible at frequencies above the cut-off-frequency. It is defined by the geometry of the metallic vessel and is determined experimentally during commissioning of the chamber. The cut-off frequency can be interpreted in different ways. On the one hand as the first fundamental mode (theoretically calculable according to Weyl's formula [10]) or as soon as enough modes have propagated in the chamber, a kind of stability criterion. The first fundamental mode was calculated to 378 MHz. For more information about the characteristics and especially the preceding simulation model, see [9]. However, since the beam dump and other components such as the antenna and thruster reduce the volume of the chamber, the resonant frequency increases slightly.

The main difference to the semi-anechoic chamber is that very high field strengths can be generated with a comparatively low feed-in power. Whereas the semi-anechoic chamber is a replica of the free space [11].

Measurement

Initial measurements were conducted with the PPT to test the operation of the devices and check the electromagnetic characteristics. Furthermore, a cross-check with the reverberation chamber was performed. As can be seen in Fig. 4, the PPT is located inside the GRP cylinder, only its electrical connections are routed out of the chamber to supply the thruster. The thruster system consists of the four PETRUS PPT and a black box containing a communication and control module. Also included is a charge and ignition unit. The cabling consists of the power supply lines, two communication

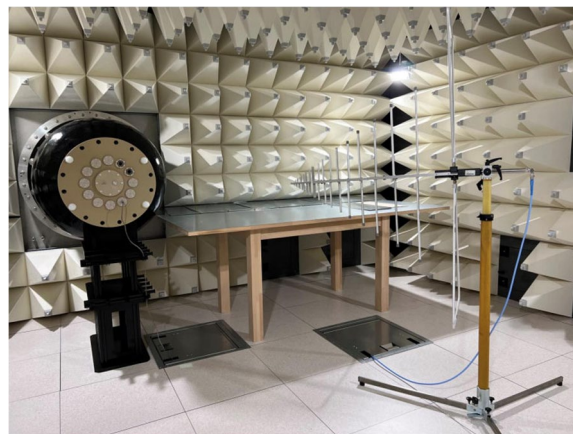


Fig. 4 Measurement setup with PPT inside GRP cylinder and antenna

cables and a ground cable. The PPT module is grounded to the semi-anechoic chamber. The mounting of the PPT is not grounded. The initial pressure of the SAC is below 10^{-6} mbar, which increases to about $7 \cdot 10^{-6}$ mbar at $q = 0.25$ sccm Xe propellant flow. The thruster is operated nominally. The PPT burns its on-board solid propellant, and the pulsed extractions here occur at 2 Hz. PPT with solid propellant have a negligible effect on the background pressure of the chamber compared to systems with gas flow such as an RIT. The temperature was not determined before, during or after the measurement.

Since the PPT is ignited at 2 Hz, this corresponds to a pulse length of 500 ms. Accordingly, the spectrum analyzer is triggered every 500 ms to sample a frequency range. This ensures that a pulse of the PPT takes place in each frequency range. The measurement therefore starts at 30 MHz and runs step by step through the frequency range up to 8 GHz, with a dwell time of 500 ms per frequency window, the step size is logarithmic, otherwise the measurement would be too time-consuming. Before starting operation and measurement, a steady state of the chamber pressure was waited for.

As shown in Fig. 5, the results include the noise caused by ambient radiation and the radiation caused by the PPT. For comparison, the results in both the semi-anechoic chamber and the reverberation chamber are shown. In the reverberation chamber, the lowest useable frequency is about 300 MHz due to the available antennas. In any case, the results in the reverberation chamber are only meaningful above 378 MHz, which is approximately the stable cut-off-frequency of the cavity. The antenna in the semi-anechoic chamber has its highest frequency at 8 GHz.

The discrepancy between the SAC and RVC results can be explained as follows: First, the background radiation between SAC and RVC facilities is different due to different methods of calculating the field strength. The lower characteristic curve of the RVC facility means that it is more sensitive compared to the SAC facility. The increased sensitivity can be recognized by the base noise, which is significantly lower in the RVC. This makes it possible to detect lower field strengths. In the reverberation chamber, the total power of the DUT is obtained by the antenna, which is increased by the amplification of cavity resonators. The energy radiated above the cutoff frequency is reflected several times in the RVC and can be damped to a lesser extent compared to the SAC setup.

In the EMC32 software module for the RVC, the antenna distance is set to 1 m, since the standards require such a distance. Since no such distance can be maintained in the

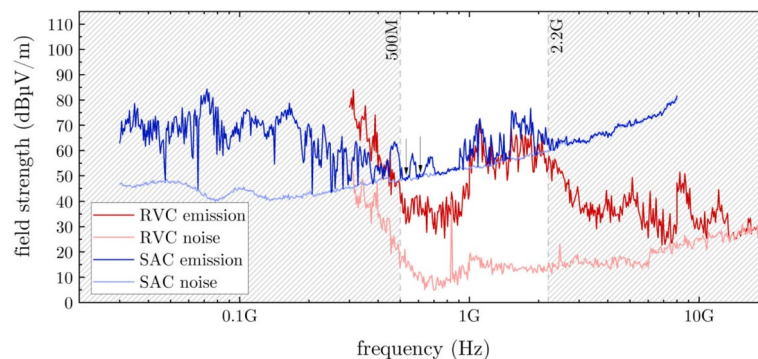


Fig. 5 Measurement results with comparison of reverberation chamber. SAC noise (light blue), PPT in SAC (blue), RVC noise (light red), PPT in RVC (red)

chamber, the measurement distances in the RVC are only virtual and therefore calculated. In the SAC, however, the distance 1.5 m was used due to calibration data of the antenna. The resulting deviation was compensated by the free space attenuation. Its calculation is done with Eqs. (1) and (2) [12]:

$$F = \left(\frac{4 \cdot \pi \cdot r}{\lambda} \right)^2 \tag{1}$$

$$F_{dB} = 10 \cdot \log_{10}(F) \tag{2}$$

where r is the distance between antenna and DUT, λ is the wavelength. To give an example for a frequency of approximately 1.1 GHz, the emissions are 74 dB μ V/m (SAC) and 100 dB μ V/m (RVC). The difference is about 26 dB and the free space attenuation is calculated to 27.25 dB. This calculation is performed over the entire frequency range and is already considered in Fig. 5. For a good overview, the background noise has been subtracted from the thrusters emissions and can be seen in Fig. 6. Comparing both plots, the SAC emissions are slightly higher than the RVC's, which is a good correlation for these measurements. Since the system is a SAC, there are no absorbers mounted on the floor. Ground reflections occur, and the conditions of free space are accordingly not quite met. This creates further interference paths to the receiving antenna, depending on its position and the wavelength. Furthermore, the GRP cylinder has not yet been conclusively investigated; currently, no attenuation or even amplification due to multipath propagation is assumed. A frequency-dependent detection is required for this. Accordingly, existing deviations will be examined more closely in the next steps.

Conclusion

In summary, the facility has been built and the measurement equipment has been set up. First measurements on the ambient radiation and a PPT were performed and compared with the results in the reverberation chamber. Due to the lack of reference values, little can be said about the quality of the PPT from an EMC point of view. The radiation

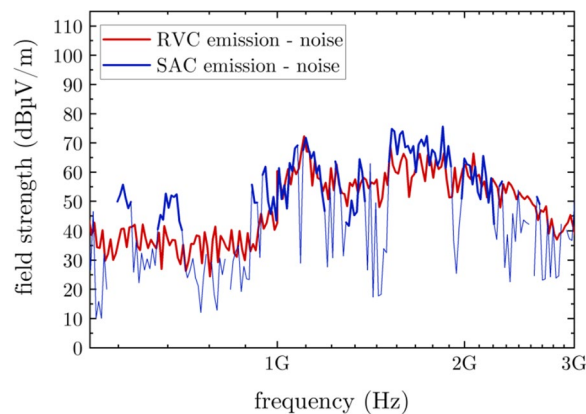


Fig. 6 SAC measurement results compared to RVC results. The ambient radiation is subtracted from the PPT data with signal-noise-ratio (SNR) > 110 % (bold lines) and SNR ≤ 110 % (narrow lines). PPT in SAC (blue), PPT in RVC (red)

pattern of the PPT is verified, due to the high agreement of the measurements in both chambers. Due to the mutual comparison of the measured values, both chambers agree and can be used. The research carried out contributes to the expansion of science insofar as new knowledge about the functionality of the chambers has been gained. Most important is the realization that the reverberation chamber can also be used for EMC measurements in the field of electric propulsion.

To give an outlook, the next steps are to eliminate the discrepancies between SAC and RVC and to perform further tests to see if both chambers can be considered equivalent. The damping/strengthening of the GRP cylinder and also the damping determination of the honeycomb are part of the future activities. When consistent and traceable results are available, the following work is planned: Comparison of two RIT and the inclusion of peripherals. The influence of wiring and its routing are also important for EMC testing for thruster assemblies. The influence and detection of thermal characteristics is also an important research topic. Depending on the dependence of the possible sizes and powers of the thrusters, tests with total systems such as CubeSats are also planned.

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Authors' contributions

Corresponding author Yannik Rover and Felix Kiefer were involved in the setup of the chamber and performed the initial measurements as well as the evaluation of the raw data. The draft of the manuscript was written by Yannik Rover and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Data are available upon reasonable request to the authors.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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References

1. Holste K, et al (2020) Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer. *Rev Sci Instrum* 91:061101. <https://doi.org/10.1063/5.0010134>
2. International Electrotechnical Commission (2018) IEC standard 60050-161-01-07: International Electrotechnical Vocabulary: Electromagnetic compatibility: Basic concepts. <https://www.electropedia.org/iev/iev.nsf/display?openform&ievref=161-01-07>
3. Zhang H, et al (2021) *Spacecraft Electromagnetic Compatibilities Technologies*. Springer. ISBN 978-981-15-4781-2. <https://doi.org/10.1007/978-981-15-4782-9>
4. Rover Y, Volkmar C (2022) Verification of a radio-frequency generator mode in a full-wave 3D EM simulation. *IEEE Aerospace Conference, Big Sky*. 978-1-6654-3760-8/22/\$31.00
5. Thueringer R, et al (2019) Test Facility for EMC-Characterization of Electric Thrusters in Operation using an evacuated Reverberation Chamber resp. an Anechoic Chamber with Vacuum Vessel and Honey Comb. IEPC-2019-A618, University of Vienna, Austria
6. Beiting EJ, et al (2003) Electromagnetic Emissions to 60 GHz from a BPT-4000 EDM Hall Thruster. *International Electric Propulsion Conference, IEPC-03-129*, Toulouse

7. Baranov SV, et al (2017) Determination of Electromagnetic Emission from Electric Propulsion Thrusters under Ground Conditions. International Electric Propulsion Conference, IEPC-2017-167, Atlanta
8. Montag C, et al (2021) PETRUS 1J pulsed plasma thruster for the 3U GreenCube mission. 72nd International Astronautical Congress (IAC), Dubai
9. Kiefer F, et al (2022) Reverberation chamber for electromagnetic compatibility testing of electric thrusters. IEPC-2022-257, Massachusetts Institute of Technology, Cambridge
10. Hill DA (2009) Electromagnetic fields in cavities. Wiley-IEEE. ISBN 978-0-470-46590-5
11. Gustrau F (2015) Elektromagnetische Verträglichkeit. Hanser. ISBN 978-3-446-44301-3
12. Gustrau F (2019) Hochfrequenztechnik. Hanser, 3. ed.. ISBN 978-3-446-45950-2

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