EMI Tests of the HEMP Thruster Propulsion System

IEPC-2013-120

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

Edward J. Beiting[1], William A. Cox[2], Kevin D. Diamant[3], Jason A. Young[4], Rostislav Spektor[5]
The Aerospace Corporation, Los Angeles, CA 90009, USA

Stefan Weis[6], Benjamin van Reijen[7]
Thales Electronic Systems GmbH, 89077 Ulm, Germany

and

Klaus Ruf[8]
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), D-53227 Bonn, Germany

Abstract: This paper describes a subset the electromagnetic compatibility measurements made on the Thales Electron Devices GmbH HEMP Thruster Module and performed at the electric propulsion laboratory at The Aerospace Corporation. The measurements included conducted emission measurements from 20 Hz to 100 MHz; radiated magnetic field measurements from 50 Hz to 250 kHz; radiated electric field measurements from 1 MHz to 18 GHz; radiated electric field measurements from 18 GHz to 50 GHz. Additionally, radiated susceptibility measurements from 1 MHz to 40 GHz with specified electric fields up to 200 V/m were made. Results from the MIL-STD 461E radiated emission measurements and the susceptibility measurements are reported.

Nomenclature

CE101/103	=	conducted emission standards under MIL-STD 461E
EMC	=	Electromagnetic Compatibility
EP	=	Electric Propulsion
FFT	=	Fast Fourier Transform
HEMP-T	=	High Efficiency Multistage Plasma Thruster
HTM	=	HEMP Thruster Module
LISN	=	Line Impedance Stabilization Network
MIL-STD	=	Military Standard (USA)
PDT	=	Pacific Daylight Time
PSCU	=	Power Supply and Control Unit
RE101/102/103		radiated emission standards under MIL-STD 461E
RGA	=	Residual Gas Analyzer
s	=	second (unit of time)
X-, L-, S-, C-	=	microwave bands = 0.3-1, 1-2, 2-4, 4-8 GHz respectively

[1] Senior Scientist, Propulsion Science Department, edward.j.beiting@aero.org
[2] Associate Technical Staff, Propulsion Science Department, william.cox@aero.org
[3] Research Scientist, Propulsion Science Department, kevin.d.diamant@aero.org
[4] Member of Technical Staff, Propulsion Science Department, jason.young@aero.org
[5] Research Scientist, Propulsion Science Department, rostislav.spector@aero.org
[6] Electric Propulsion System Manager, Plasma Devices, stefan.weis@thalesgroup.com
[7] Electric Propulsion Components R&D Manager, Plasma Devices, benjamin.reijen@thalesgroup.com
[8] Program Manager, DLR, klaus.ruf@dlr.de

I. Introduction

The HEMP Thruster Propulsion System has been under development for more than a decade. It is a new design concept for plasma thrusters, which exploits mature TWT technology in a permanent magnet, multi-stage, drift tube configuration.[1] In preparation for its on-orbit use, comprehensive Electromagnetic Compatibility (EMC) measurements were carried out at the EMC electric propulsion test facility at The Aerospace Corporation in El Segundo CA. In particular, measurements included radiated susceptibility measurements from 1 MHz to 40 GHz with specified electric fields up to 200 V/m, conducted emission measurements (CE101/103) from 20 Hz to 100 MHz; radiated magnetic field measurements (RE101) from 50 Hz to 250 kHz; radiated electric field measurements (RE102) from 1 MHz to 18 GHz; radiated electric field measurements (RE103) from 18 GHz to 50 GHz. In addition high resolution, high sensitivity radiated emissions measurements were made over selected bands. Only the results of the radiated susceptibility measurements and the MIL-STD radiated emission measurements will be reported in this paper.

Radiated Susceptibility (RS) and Radiated Emission (RE) measurements were performed according to MIL-STD 461E specifications on the Thales HTM (HEMP Thruster Module). The HEMP-T was operated through the Power Supply and Control Unit (PSCU) and Flow Control Unit (FCU). All measurements were made with the thruster operating at its nominal operating parameters. For the susceptibility measurements, the HTM was irradiated with prescribed field strengths up to 200 V/m for frequencies between 1 MHz and 40 GHz. For these measurements, the field was stepped in frequency, held for 3 s, and after this dwell period, critical thruster parameters were recorded.

Electric field radiated emission (MIL-STD 462E RE102/103) was measured on the cathode side of the thruster, 1m from the thruster centerline and for vertical (10 kHz to 50 GHz) and horizontal (30 MHz to 50 GHz) polarizations. Between 1 – 18 GHz the RE102 measurements also were made on the opposite side and at a third position in front of the thruster, viewing only the thruster plume.

II. Facility and Configuration

A. EMC Facility

The Aerospace Corporation's EMC facility is shown in Figure 1. The small (0.9 m diam. and 1.5 m long) all-dielectric vacuum tank houses the thruster. This completely nonmetallic and noncarbon tank is constructed of S2 glass that has a relatively low dielectric constant and is largely transparent to electromagnetic radiation. This fiberglass tank mates to a stainless steel vacuum chamber, which is pumped with four cryotubs and four reentrant cryopumps. A high-power thruster placed in this chamber is usually mounted on a water-cooled plate to control its temperature. A more complete description of the characteristics of the dielectric tank is available [2].

The small size of the tank allows antennas to be placed outside the vacuum to the side and behind the thruster at a distance of one meter from the thruster as required by MIL-STD 461E. Because the antennas are outside the vacuum, there is no antenna-plasma interaction. Additionally, the antennas required for recording emission between 10 kHz and 18 GHz (or higher frequencies) can be positioned sequentially, eliminating the possibility of antenna-antenna interaction.

Ambient electromagnetic radiation leaks into the main vacuum tank through openings and cables attached to equipment in the tank. Subsequently, this radiation leaks into the anechoic room through the fiberglass tank orifice and is apparent in the 20–200 MHz frequency band, where there is room resonance (see background traces in Figures 7 and 8). In the most cases this radiation was at least 10 dB below the measured signal.

A 5.5m x 4.25m x 3m semi-anechoic room surrounds the dielectric tank to shield the thruster from the ambient electromagnetic environment. It provides >100 dB shielding from 14 kHz - 18 GHz and is designed to be MIL-STD 285 and NSA 65-5 compliant. The plume of the thruster exhausts into the main vacuum tank, terminating on a beam dump comprising a series of 0.6-m-high aluminum pyramids covered with grafoil to reduce sputtering by the high-energy xenon ions and reduce scattering of electromagnetic radiation from the thruster by the main tank at higher frequencies. A complete description of this facility, including performance measurements, is published [3].

Analyzers, receivers, and custom-built time-domain instruments record the radiation emanating from the thruster. Below 18 GHz, the instruments connect sequentially to a series of antennas through a panel in the semi-anechoic room using a two-section semi-rigid cable with known attenuation. Above 18 GHz, a smaller receiver situated in the anechoic room connects sequentially through one of two short cables to a series of low-noise amplifiers (LNAs) mated directly to octave horns.

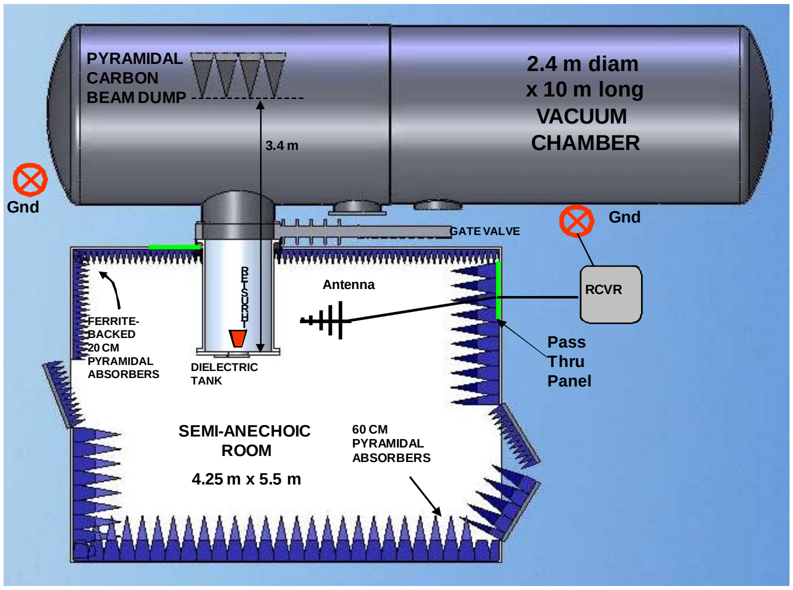

Figure 1. Facility used to make EMC measurements on the HEMP-T thruster system.

B. HTM Installation

The HTM (represented by the HTM-EM4) was electrically isolated inside the dielectric vacuum tank. The PSCU (represented by the latest version of the PSCU-EBB with full functionality) was located outside the vacuum chamber and the semi-anechoic room. The interconnecting harness was fed through the vacuum chamber with dedicated feed-throughs. The PSCU was supplied via a LISN that is powered by a power supply, also located outside the anechoic room, to avoid introduction of noise by this commercial device. The electrical configuration is shown in Figure 2.

The thruster assembly was attached to a vertical aluminum bracket positioned so that the centerline of the thruster coincided with the centerline of the fiberglass tank. Water-cooling was supplied to the thruster and the water temperature varied between 20^{o}C and 21^{o}C for all operating conditions. Propellant lines were routed along the bottom of the dielectric chamber underneath a fiberglass plate.

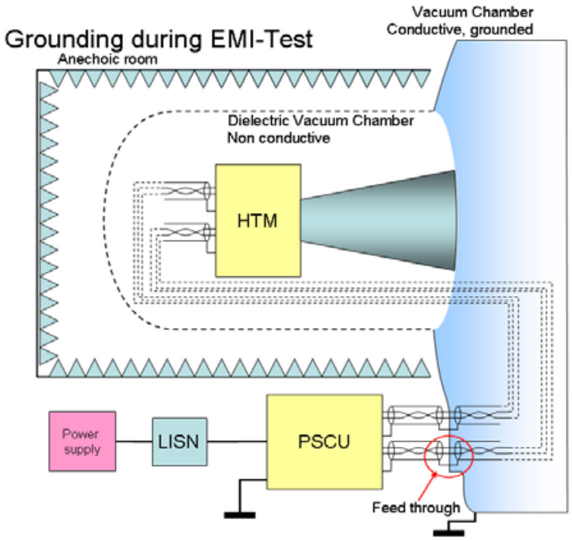

Figure 2. Electrical configuration of the HTM.

C Vacuum System

Seven of eight cryopumps were operated while measurements were made, resulting in a measured xenon pumping speed in the main chamber of approximately 10^5 liter/s while the HEMP-T thruster was operating (xenon flow rate of 1.9 mg/s). A history of the chamber pressure after the thruster was installed in shown in Figure 3. This plots the gauge pressure reading in mbar as a function of date. The no-load background pressure is accurate but the pressure shown when the thruster is operating must be reduced by the factor (for Xe) of 0.348. Thus the pressures shown as 8 x 10^{-6} mbar should be read as 2.8 x 10^{-6} mbar. Initial pump out of the chamber was a 3x cycle of pump out to approximately 250 mbar and vent with nitrogen. The final vent after the campaign was done with nitrogen.

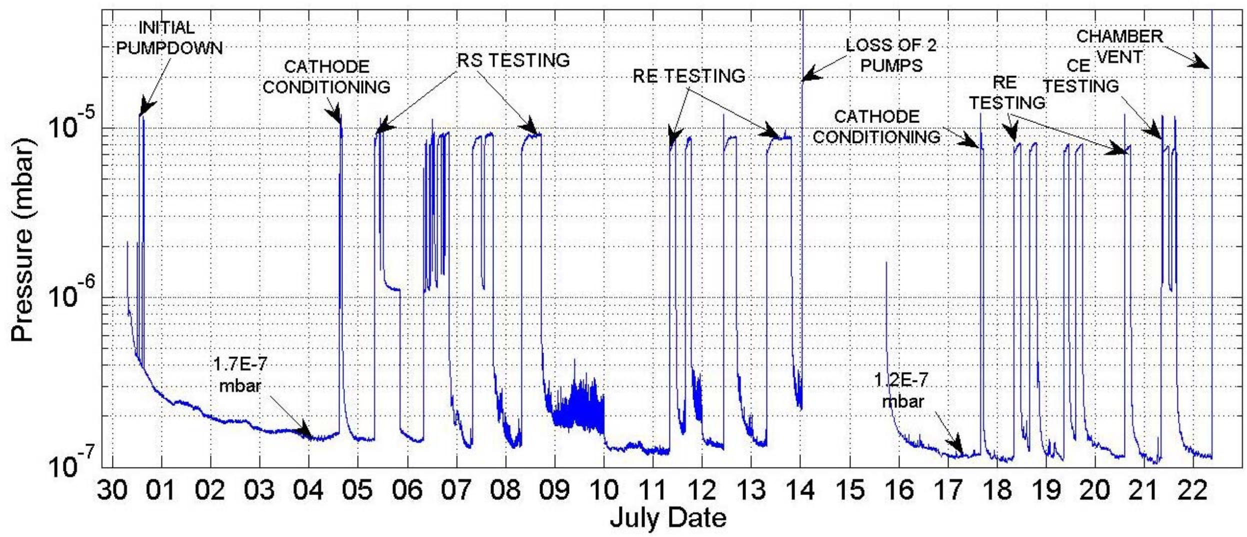

Figure 3. History of chamber pressure during testing campaign. The low pressures values are correct; the high values are xenon pressures and must be reduced by a factor of 0.348.

The main activities and events are labeled on Figure 3. The initial cathode conditioning was delayed for three days while waiting for the pressure to decrease to below the specified value of 2 x 10^{-7} mbar. This delay was caused by water out-gassing from the wall of the chamber. Near 01:00 PDT on 13 July 2011, two of the cryo-pumps malfunctioned causing a pressure increase to 2 x 10^{-3} mbar. This required a repair, pump regeneration, and cathode reconditioning. An SRS RGA300 RGA was employed for leak testing and to characterize chamber constituents.

III. Radiated Susceptibility Studies

To ensure that the HTM does not malfunction in a high electric field environment, the thruster was subjected to specified electric field strengths as a function of frequency while monitoring key thruster parameters. The electric field strengths were created by transducers that were driven by the output of a series of high-power broad-band microwave amplifiers. These amplifiers were excited by a modulated signal generator (frequency synthesizer) that was digitally stepped in frequency and power. A synopsis of the signal generators, amplifiers, and transducers used in the 1 MHz to 40 GHz frequency range over which the measurements were taken is presented in Table 1. In all cases the modulator was an Agilent 33220A Function Generator.

Table 1

Frequency	Synthesizer	Amplifier	Transducers
1-20 MHz	Agilent 33220A	AR 100A100	AT3000 Field Generator
20-100 MHz	MG3696A*	AR 100A100	EMCO Biconical 3109P
100-200 MHz	MG3696A*	AR 150W1000	EMCO Biconical 3109P
200-1000 MHz	MG3696A*	AR 150W1000	EMCO 3601 Double Ridge Horn
1.0-2.6 GHz	MG3696A*	AR 500TG2	FXR L638A, FXR R638A
2.6-8 GHz	MG3696A*	IFI-T82-300	MCS 383, NARDA 643, FLANN 13240-20, 15240-20
8-18 GHz	MG3696A*	LOGI-A350/IJ	FLANN 15240-20, 16240-20, 18240-20
18-26.5 GHz	MG3696A*	IFI-T2618-40	FLANN 20240-20
26.5-40 GHz	MG3696A*	IFI-T4026-50	FLANN 22240-20

*Anritsu

The following procedure was used to determine the required power from the synthesizer. First, a calibrated field probe was place at the expected location of the thruster inside the dielectric tank (on centerline of the dielectric tank, 30 cm from the back plane); the back flange of the tank was then installed. Second, the transducer (field generator, antenna, or horn) was place 100 cm to the side of the tank centerline, parallel to and 30 cm from the tank back plane and shown in the left side of Figure 4. A photograph of the isotropic field probe in the dielectric tank (used for the higher frequencies) is given in the right of this figure. Finally, the 30% square-wave-modulated power of the synthesizer was adjusted to produce an RMS field value (measured by the field probe) greater than that specified for the exciting frequency. This procedure was repeated for many frequencies across each band, for each experimental setup listed in Table 1. This method was used to create tables of frequency, power, and dwell time (3s) that were used later to computer control the synthesizer during testing.

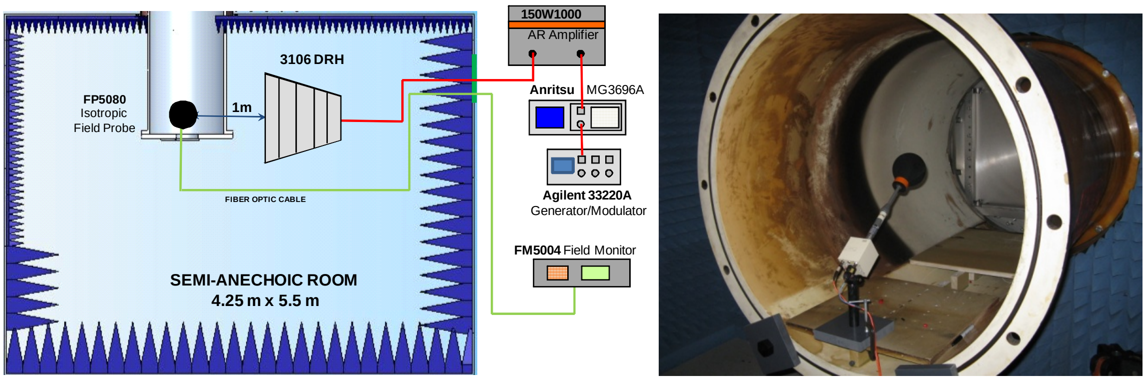

Figure 4. Left: Calibration Setup. Right: View of isotropic field probe in dielectric tank.

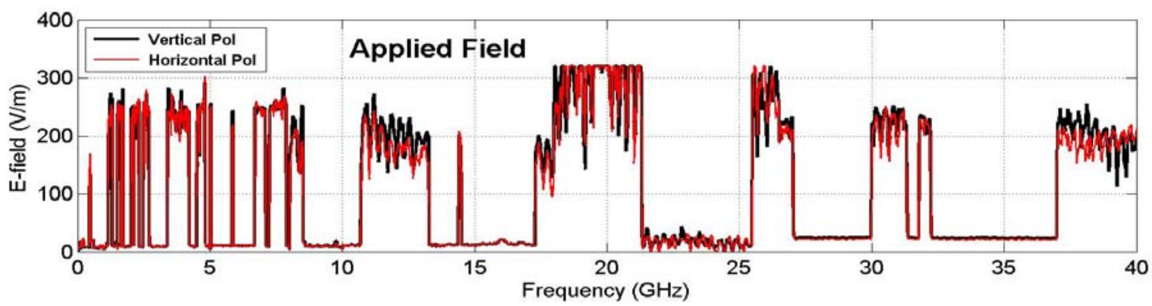

Figure 5. Applied Field Strengths. - Contains Data provided by courtesy of OHB System AG -

The field strengths applied for this test are shown graphically in Figure 5. The computer, reading the values from the table described above, set the frequency and power output of the modulated signal generator and after dwelling for 3 seconds, recorded digitized values of HV line, HV return line (EP ground), and anode current through a filter box. These are the parameters most correlated with thrust. This system was calibrated by injecting a range of known voltages and currents with values bracketing the expected values between the PSCU and the HV connector box and recording the digital values created by the data acquisition module. These values were then interpolated using a linear regression fit to generate the measured values reported. The output from field probe monitor, shown in Figure 4, was recorded during the measurements and used as a qualitative measure of the field that was irradiating the thruster. Periodically the computer directed an oscilloscope to acquire a time trace of the anode current that was recorded as a frequency spectrum (FFT). All monitored thruster parameters remained within their limits during the irradiation of the HTM.

IV. Radiated Electric Field Measurements

A. Spectral Scans

Two series of measurements were taken. The first series comprised spectra taken using MIL-STD 461E RE102 specifications. These were acquired in both vertical (10 kHz–18 GHz) and horizontal (30 MHz–18 GHz) polarization. RE102 specifications specify resolution bandwidths (RBWs), maximum scan rates, and peak detection mode. The second series was taken from 18–50 GHz. Again, these spectra were taken with MIL-STD specifications with the exception that -3dB RBWs were used instead of the -6dB RBWs specified in RE103. A -3dB RBW is about 50% broader than the corresponding -6 dB RBW.

Electromagnetic radiation for the spectral scans was sensed by antennas that meet MIL-STD 461E requirements, with the exception that the large double-ridge horn was replaced by a log-periodic antenna for the 200 – 1000 MHz band. Signals were routed via cables of known attenuation through a panel in the anechoic room to the microwave receivers, analyzers, and time domain instrumentation.

The instrumentation, bands, bandwidths, and scan rates are listed in Table 2. Nominally, below 1 GHz the antennas are in the near field; above this frequency they are in the far field. Both vertically and horizontally polarized emission data were acquired for all antennas with the exception of the rod antenna that is used only in the vertical orientation.

Table 2.
Instrumentation and MIL-STD 462E Parameters for Spectral Scans

Freq Range(MHz)	RBW (kHz)	Scan Rate(s/MHz)	Analyzer*	LNA	Antenna
0.010-0.150	1 (6dB)	15	RS ESIB 26	None	Rod
0.150-30	10 (6dB)	1.5	RS ESIB 26	None	Rod
30-200	100 (6dB)	0.15	RS ESIB 26	HP 87405A	Biconical
200-1000	100 (6dB)	0.15	RS ESIB 26	HP 87405A	Log Periodic
1000-12500	1000 (6dB)	0.015	RS ESIB 26	Miteq 39dB G/2.7dB	DR Horn
12500-18000	1000 (6dB)	0.015	RS ESIB 26	Miteq 39dB G/2.7dB	1218 SGH
18000-26500	1000 (3dB)	0.015	Agilent	Miteq 38dB G/2.6dB	1826 SGH
26500-40000	1000 (3dB)	0.015	Agilent	Miteq 40dB G/3.5dB	2640 SGH
40000-50000	1000 (3dB)	0.015	Agilent	Miteq 35dB G/5.5dB	4060 SGH

*RS = Rohde Schwarz

Care was exercised to ensure that good electrical grounding techniques were used. The coaxial cables from the antennas to the receivers were routed through the anechoic room panel using isolated feed-throughs. All instrumentation was powered through an isolation transformer and grounded at a single point isolated ground marked in red nearest in the EMC instrumentation in Figure 1.

RE spectra are presented for position 1 (defined in Figure 6) in four frequency segments: 10 kHz – 30 MHz, 30 – 1000 MHz, 1 – 18 GHz; and 18 – 50 GHz. Spatial resolution is possible for frequencies where the wavelength is smaller than the experimental geometries (about 1 m or a frequency of 300 MHz), so spectra were taken at position 2 to observe any asymmetry in emission caused by the cathode. One interval from 1 – 18 GHz using RE102 specifications was recorded at position 3 to observe emission in front of the thruster and is compared to comparable measurements at positions 1 and 2.

It should be noted that, by necessity, the emission shown in all figures are sampled and plotted at intervals lower than the acquired data sampling. In all cases the plotted resolution is greater than that required by MIL-STD 462E. The sampling method used was a function of the detection method used during acquisition. For data recorded in peak detection mode, the peak value in a sampled interval is chosen and plotted. All data were recorded with a resolution of 2 data points per RBW as listed in column 2 of Table 4-1, or greater resolution for the high sensitivity scans.

The results of the emission measurements are present in Figures 7 – 10. In Figure 7, the emission in the 10 kHz – 30 MHz interval saturated the preamplifier on the active rod antenna and thus required that the data be taken with a passive rod. The background was acquired using the active rod, which was required to measure the much lower background values below 1 MHz. The difference between emission and background varied between 10 dB near 20 MHz and 80 dB near 200 kHz.

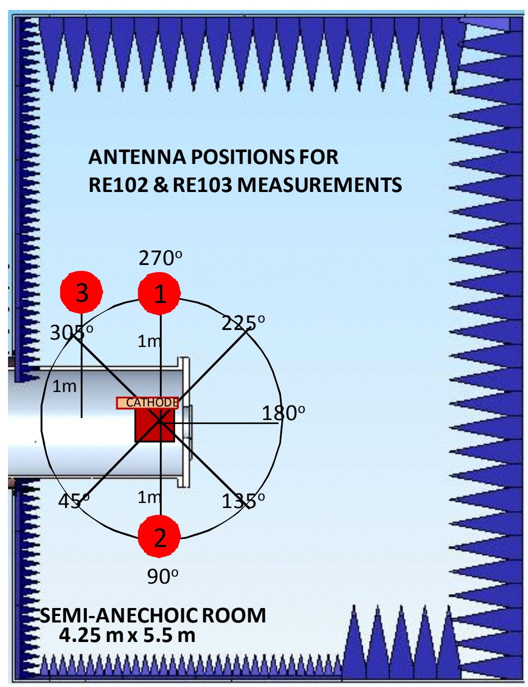

Figure 6. Antenna Positions for > 1 GHz Spectra

Figure 8 show that between 30 MHz and 1000 MHz, the horizontally polarized emission is 5 – 10 dBμV/m above the vertically polarized emission with an exception of the emission near 200 MHz.

The plots presented in Figure 9 show strong emission in the L, S, C, and X bands. This behavior is typical of Hall-type thrusters.[4,5] There is a decrease in emission between 10 dBμV/m (purely incoherent emission) and 15 dBμV/m (mix between coherent and incoherent emission) when the bandwidth is decreased a factor of 10 (from 1 MHz to 100 kHz). Purely coherent emission decrease 20 dB per decade decrease in RBW and often indicates that the radiation is pulsed. Figure 9 also compares the emission taken with MIL-STD 461E specifications from 1 – 18 GHz for the three positions shown in Figure 6. The emission registered from the position closest to the cathode (Position 1) shows higher emission in the L-band and the X band in vertical polarization. In horizontal polarization, emission registered from Position 2 shows slightly higher levels. The emission registered in front of the thruster (Position 3) does not differ significantly for the emission registered from the sides of the thruster.

Finally, Figure 10 shows no emission from 18 – 50 GHz above the sensitivity of the instrumentation, which is 25 – 40 dB below the MIL-STD 461E RE103 limits.

V. Conclusions

A full electromagnetic compatibility characterization of the Thales HEMP-T Thruster Module (HTM) was made. The electric field susceptibility results and the MIL-STD 461 RE102/103 electric emission results are reported here. The HTM showed no anomalous behavior when radiated with electric fields as specified with fields as high as 200 V/m and at frequencies up to 40 GHz. The electromagnetic emission from the thruster is characteristic and its spectrum is comparable to that of Hall thrusters.

Acknowledgements

Preparation of this manuscript was supported under The Aerospace Corporation's Sustained Experimentation and Research for Program Applications program. The HEMP-Thruster Electric Propulsion System development was carried out on behalf of the Space Administration of the German Aerospace Center (DLR e.V.) with funds from the Federal Ministry of Economics and Technology under contract number 50 RS 0803. The authors are responsible for the contents of the publication.

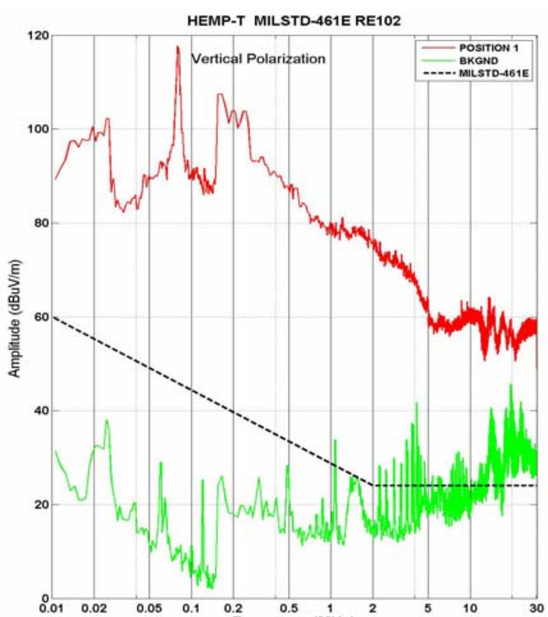

Figure 7. RE102 emission 10 kHz – 30 MHz.

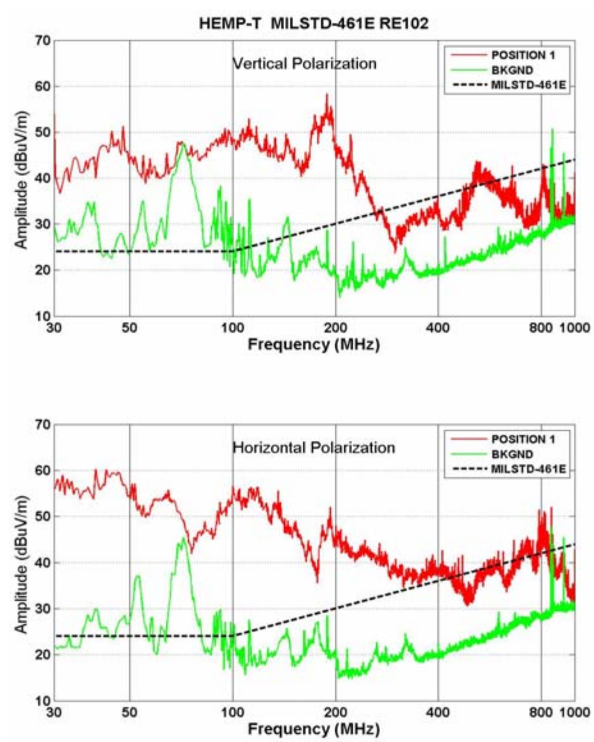

Figure 8. RE102 emission 30 MHz – 1000 MHz.

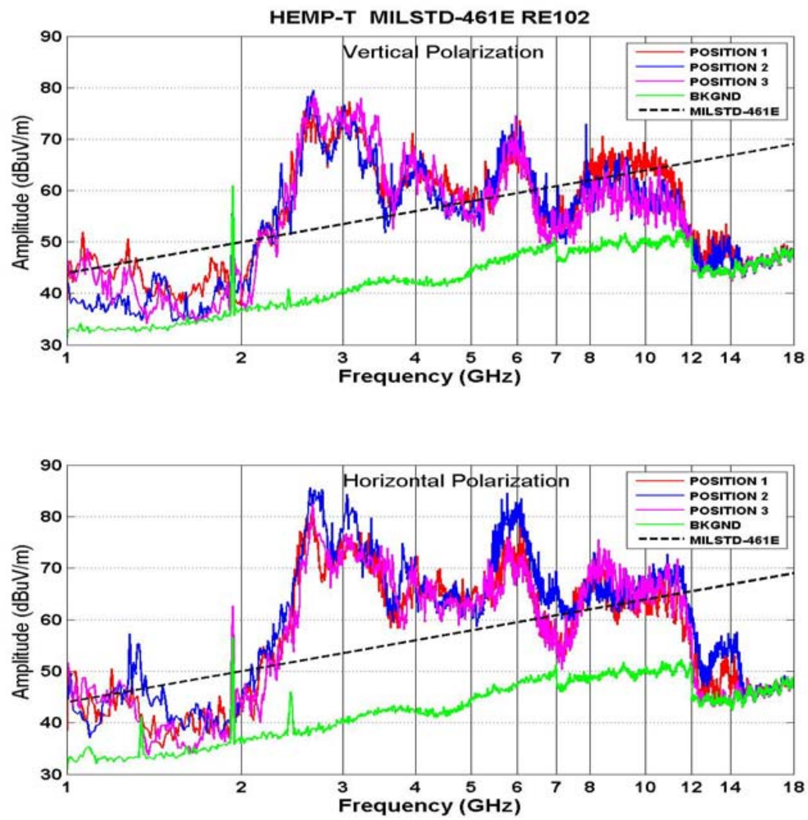

Figure 9. RE102 emission 1 GHz – 18 GHz.

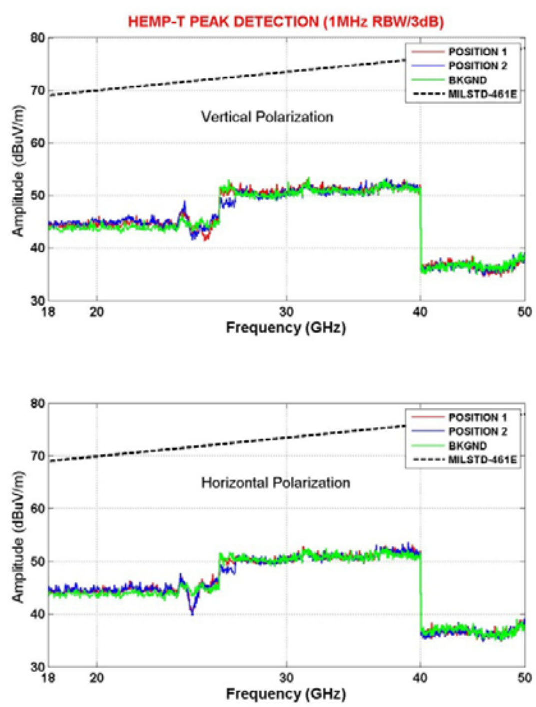

Figure 10. RE103 emission 18 GHz – 50 GHz.

References

1. Koch, N., Schirra, M., Weis, S., Lazurenko, A., van Reijen, B., Haderspeck, J., Genovese, A., Holtmann, P., Schneider, R., Matyash, K., and Kalentyev, O., “The HEMPT Concept - A Survey on Theoretical Considerations and Experimental Evidences,” *IEPC Meeting Paper IEPC-2011-236*, Wiesbaden Germany, 2011.
2. Beiting, E. J., “Design and Performance of a Facility to Measure Electromagnetic Emissions from Electric Satellite Thrusters,” *AIAA Meeting Paper AIAA-2001-3344*, Salt Lake City, UT, 2001.
3. Beiting, E. J., and Garrett, M. L, “Facility for High-Fidelity Electromagnetic Compatibility Studies of Electric Thrusters,” *AIAA Meeting Paper AIAA-2007-5329*, Cincinnati, OH, 2007.
4. Beiting, E. J., Garrett, M. L, Pollard, J. E., Pezet, B., and Gouvernayre, P.,“Spectral Characteristics of Radiated Emission from SPT-100 Hall Thrusters,” *IEPC Meeting Paper IEPC-2005-221*, Princeton, NJ, 2005.
5. Beiting, E. J., Garrett, M. L, and Pollard, J. E., “Spectral and Temporal Characteristics of Electromagnetic Emissions from the BPT-4000 Hall Thruster,” *AIAA Meeting Paper AIAA-2006-5262*, Sacramento, CA, 2006.