Electromagnetic Emissions from a BHT-200 Hall Thruster*

Edward J. Beiting and James E. Pollard
The Aerospace Corporation
P. O. Box 92957, M5-754
Los Angeles, CA 90009-2957
310-336-7035/310-336-4023
edward.j.beiting@aero.org/james.e.pollard@aero.org
and
Bruce Pote
Busek Company
11 Tech Circle
Natick, MA 01760
508-655-5565
bpote@busek.com

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Abstract

Radiated electric fields were measured from a BHT-200 Hall thruster from 10 kHz to 18 GHz following MIL-STD 461E (RE102) specifications. The thruster, operated by a laboratory power supply, was located in a fiberglass vacuum tank which was enclosed in shielded semi-anechoic room. The measurements were made for discharge potentials of 225, 250, 275, and 300 volts and anode flow rates of 0.80 0.90, 0.94, and 1.0 mg/s (150 – 240 W discharge power) as well as for several cathode flow rates. For all flow rates and discharge voltages, emission exceeded MIL-STD 461E limits between 10 kHz to 200 MHz. However, for the anticipated thruster operating point (250 V, 0.94 mg/s), electromagnetic emissions remained below MIL-STD 461E limits between 350 MHz and 18 GHz. Generally, electromagnetic emission decreased with increasing anode flow rate below 500 kHz and between 15 and 30 MHz but increased with anode flow rate between 1 and 5 MHz. Above 30 MHz, there was no variation of emission with anode flow rate. When the thruster operated at 250 V and 0.94 mg/s anode flow rate, emission decreased with increasing cathode flow rate below 500 kHz. There was no significant variation of emission with discharge voltage above 500 kHz. There was no appreciable difference between spectra taken with the high frequency blocking filter located inside a shielding box next to the thruster and spectra taken with the filter located outside the vacuum chamber. Spectra of the anode current oscillations recorded between 1 kHz and 50 MHz were similar to the radiated spectra and show minimal variation with cathode flow rate.

Purpose and Scope

The on-board propulsion system for TechSat 21, an Air Force Research Laboratory technology demonstration mission of a formation of micro-satellites, is a single BHT-200 thruster. This 200 watt Hall thruster will operate at 35% efficiency with a specific impulse of 1300 sec and will be capable of small impulse bits in order to maintain the inter-satellite separation required for on-orbit formation flying. [1]

As part of this program, radiated electric fields were measured from an engineering model BHT-200 thruster. [2] The fields were recorded from 10 kHz to 18 GHz following MIL-STD 461E specifications. The thruster was operated with a laboratory power supply (through a high frequency blocking filter) and a

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Table 1
Main Test Matrix

No.	Discharge Voltage	Discharge Current (A)	Power (W)	Anode Flow (mg/s)	Cathode Flow (mg/s)
1	OFF	0.67	0	OFF	OFF
2	225	0.67	151	0.8	0.064
3	250	0.67	168	0.8	0.064
4	275	0.67	184	0.8	0.064
5	300	0.77	203	0.8	0.064
6	225	0.77	173	0.9	0.072
7	250	0.77	190	0.9	0.072
8	275	0.77	209	0.9	0.072
9	300	0.81	240	0.9	0.072
10	225	0.81	185	0.94	0.074
11	250	0.81	205	0.94	0.074
12	275	0.81	226	0.94	0.074
13	300	0.86	243	0.94	0.074
14	225	0.86	196	1.0	0.080
15	250	0.86	218	1.0	0.080
16	275	0.86	239	1.0	0.080
17	300	--	--	1.0	0.080

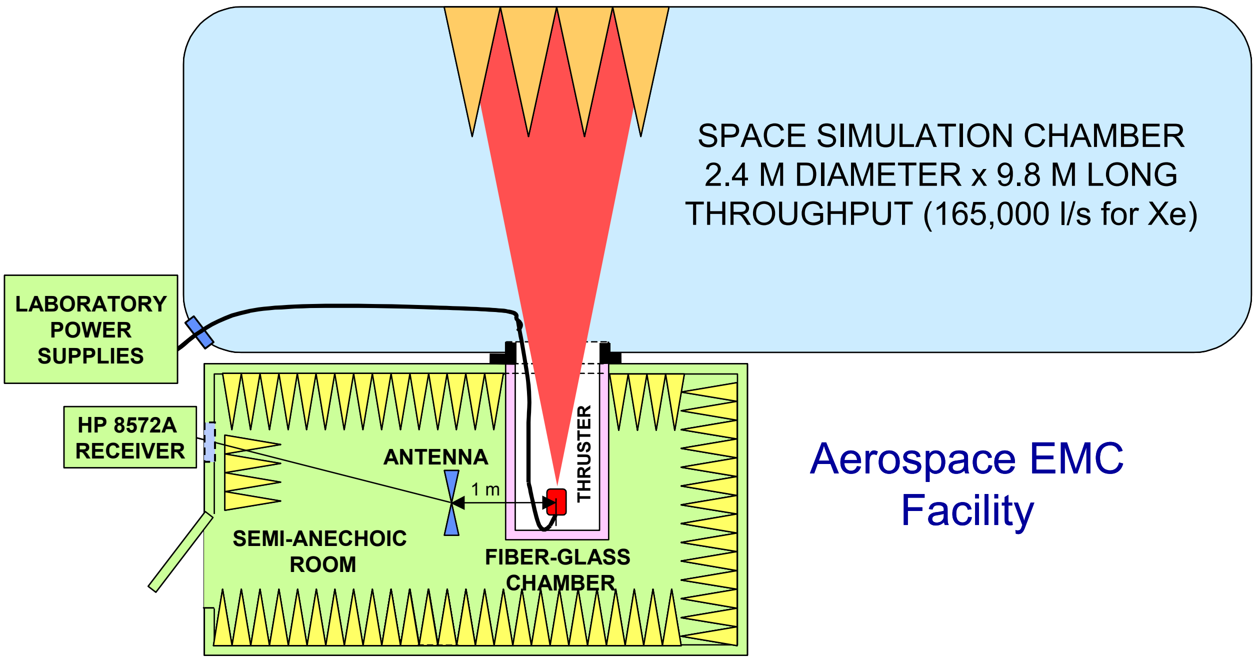
Table 2
Cathode Flow Test Matrix

No.	Discharge Voltage	Anode Flow Rate (mg/s)	Cathode Flow Rate (mg/s)	Power (W)
1	250	0.94	0.075	202.5
2	250	0.94	0.0564	202.5
3	250	0.94	0.0376	0
4	250	0.94	0.094	202.5
5	250	0.94	0.1128	202.5
6	OFF	OFF	OFF	0

laboratory xenon flow controller. Spectra of the anode current oscillations were also recorded for several operating conditions. Previous measurements of radiated emissions from Hall thrusters have been made at NASA Glenn Research Center and The Aerospace Corporation. [3-5]

The purpose of the tests was to survey the radiated field as a function of discharge voltage, anode flow rate, cathode flow rate, and discharge filter configuration. The main study measured emissions for the operating points shown in Table 1. This matrix was repeated nine times (for five frequency intervals and two antenna polarizations) to generate a complete data set. The cathode flow rate was kept at 8% of the anode flow rate and the magnetic field was adjusted to minimize the discharge current. The powers listed in Table 1 are examples of the measured values.

A second study measured the emission from the thruster for setting No. 11 in Table 1 while the cathode flow rate was varied. The test matrix for this study is shown in Table 2. The thruster operation was too unstable at setting No. 17 of Table 1 and No. 3 of Table 2 for data acquisition. Finally, a third study repeated operating point No. 11 in Table 1 with the discharge filter components outside the vacuum system.



Facility and Configuration

Figure 1. Layout of the facility (not to scale) used to measure electromagnetic emissions from electric thrusters.

The Aerospace Corporation EMC facility comprises three components. The first is a small, all-dielectric vacuum tank that houses the thruster. This fiberglass tank is transparent to electromagnetic radiation and mates to a large vacuum stainless steel chamber that has a xenon pumping capacity of 165,000 liter/sec. For this test, the pumping speed was 95,000 l/s because only three of the five cryo-pumps were used. The second component is a semi-anechoic room that surrounds the dielectric tank to shield the thruster from the ambient electromagnetic environment. This room is lined with 0.6 m high pyramids that absorb radiation from the thruster at frequencies higher than 80 MHz in order to mitigate reflections from the metallic walls of the room. The final component is a calibrated receiver that records the radiation emanating from the thruster. The receiver connects to series of antennas through a panel in the semi-anechoic room using a two-section semi-rigid cable with known attenuation. The arrangement of these components is shown in Figure 1.

The cylindrical dielectric vacuum tank is 0.9 meter in diameter and 1.8 meter in length. This small size 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 461/462. Because the antennas are placed outside the vacuum, there is no concern with 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.

The pyramid-lined 5m x 3m x 3m semi-anechoic room surrounding the fiberglass tank provides >100 dB shielding from 14 kHz - 18 GHz (MILSTD 285 and NSA 65-5 compliant) and has an interior wall absorption of <-6 dB (80-250 MHz) and -30 dB above 250 MHz. A modular design with free standing ceiling allows sections of the walls of the room to be removed to allow complete access to the main vacuum tank when EMC measurements are not required. The

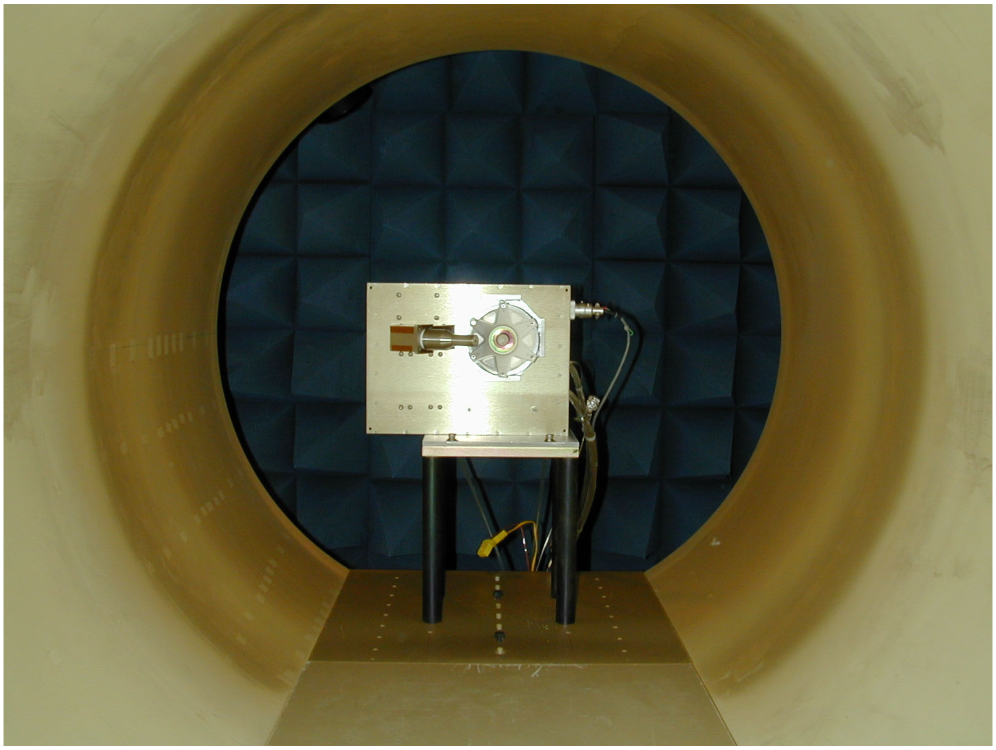


Figure 2. BHT-200 on water cooled aluminum mounting plate with filter box behind the thruster. The back of the fiberglass tank is removed allowing the absorbing pyramids in the anechoic room to be seen.

vacuum tank that houses the thruster, all bolts, fittings, cooling lines, and support fixtures that are located inside the semi-anechoic room are fabricated of electrically non-conducting materials.

As shown in Figure 2, the BHT-200 thruster was mounted on a water-cooled aluminum plate approximately the same size as of the bottom of the thruster to ensure that little electromagnetic scattering profile is added to the assembly. The water-cooled plate remained below 25^o C for all operating conditions. All support structures, fixtures, and tubing attached to the mounting plate were nonmetallic. The back of the thruster was less than 25 cm from the inside surface of the end cap of the dielectric tank; the axis of the thruster was aligned along the axis of the dielectric tank. Shielded cables and propellant lines were routed along the bottom of the dielectric chamber underneath a fiberglass plate to a vacuum feed-through in the main chamber.

The plume of the thruster exhausted into the main vacuum tank, terminating on a beam dump comprising an array of 0.6 m high aluminum pyramids covered with flexible graphite to reduce sputtering by the high energy ions. The pyramidal design of this conducting beam dump serves to reduce scattering of electromagnetic radiation from the thruster by the main tank at frequencies > 80 MHz.

Electromagnetic emission was sensed by antennas that meet MIL-STD 461/462 requirements. Signals were routed using calibrated cables through a panel in the anechoic room to a Hewlett Packard Model 8572A microwave receiver. This receiver was controlled by a computer that also stored the data for later processing by custom software. Preamplifiers, which can be used to increase the sensitivity of the receiver (lower the noise floor seen in the data figures below) and to assure that lower noise requirements of MIL-STD 461E can be met, were not necessary for these tests. Details of the data acquisition procedure and additional information on the EMC facility have been published [5].

With the thruster operating at nominally 200W (250V, 0.8 A, total xenon flow of 1 mg/s), the pressure

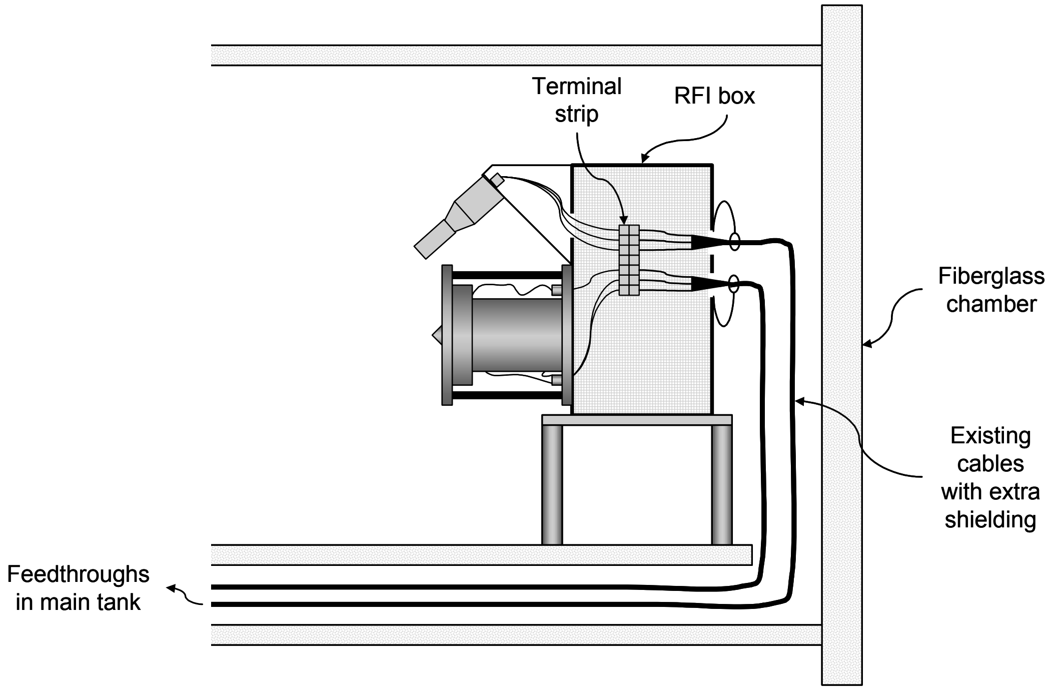


Figure 3. Shielding configuration for the BHT-200 tests. Filter components in the RFI box are not shown.

measured in main chamber was 5.6 x 10^{-6} T (corrected to 1.95 x 10^{-6} T for Xe). Pressures behind the thruster in the dielectric chamber were about two times higher than the values measured near the cryo-pump.

Care was taken to isolate the discharge current oscillations using a filter circuit attached to the back of the thruster in the approximate position that would be occupied by the PPU. Double shielded cables were routed from this box, under a fiberglass floor in the fiberglass tank through the wall of main vacuum chamber to the power supplies as shown in Figure 3.

The discharge filter was located in the RFI box for the main series of tests (Tables 1 and 2). This filter was later removed and placed between the vacuum feedthrough and the power supplies. The latter arrangement permits the anode current oscillations to be measured using a clip-on probe.

Radiated Electric Field Measurements

All radiated field measurements were made using HP 85689A software, a recently calibrated HP 8572A Option 462 receiver, calibrated antennas, and cables with known (measured) attenuation. Measurements of the radiative electric field were made following the specifications in RE102 of MIL-STD 461E.

The emission from a band for each element in the test matrix and the background emission from that band were measured before reconfiguring for the next band. Calibration of the receiver was performed for all bands at the beginning of each day's measurements.

The composite electric field spectra are presented in Figures 4-13, and Table 3 lists the test parameters for each spectrum. Each figure displays the data, background, and 461E limit line. Data from the main test matrix (Figures 4 - 11) were grouped by flow rate rather than by discharge voltage because there was less variation with discharge voltage. The horizontally polarized data begin at 30 MHz because the rod antenna can be used only in vertical polarization. All values displayed above 85 dB μV/m on these figures are inaccurate. The actual fields have values that are less than the values shown.

Caution should be exercised when comparing these data with measurements made using MIL-STD 461C or earlier specifications. Under these earlier provisions, broadband measurements are taken with an unspecified (but specific) bandwidth and then normalized to a 1 MHz bandwidth; narrow band measurements are also acquired but are not displayed

Table 4
List of Composite Electric Field Spectra

Figure No.	Variable	Discharge Voltage (V)	Anode Flow Rate (mg/s)	Antenna Polarization	Frequency Range
4	Anode Flow	225	0.8, 0.9, 0.94, 1.0	Vertical	10kHz – 18 GHz
5	Anode Flow	250	0.8, 0.9, 0.94, 1.0	Vertical	10kHz – 18 GHz
6	Anode Flow	275	0.8, 0.9, 0.94, 1.0	Vertical	10kHz – 18 GHz
7	Anode Flow	300	0.8, 0.9, 0.94	Vertical	10kHz – 18 GHz
8	Anode Flow	225	0.8, 0.9, 0.94, 1.0	Horizontal	30 MHz – 18 GHz
9	Anode Flow	250	0.8, 0.9, 0.94, 1.0	Horizontal	30 MHz – 18 GHz
10	Anode Flow	275	0.8, 0.9, 0.94, 1.0	Horizontal	30 MHz – 18 GHz
11	Anode Flow	300	0.8, 0.9, 0.94	Horizontal	30 MHz – 18 GHz
12	Cathode Flow	250	0.94	Vertical	10kHz – 30 MHz
13	Filter Position	250	0.94	Vertical	10kHz – 18 GHz

normalized to a frequency bandwidth. MIL-STD 461E specifies bandwidths at a 6 dB width and requires that data not be displayed normalized to a frequency bandwidth. When the spectra of the (noise) signals are broader than the resolution bandwidths of the spectrum analyzer, increasing the bandwidth of the analyzer increases the signal registered. If the noise is purely incoherent (Gaussian noise), the noise displayed increases linearly with bandwidth or a 10x increase in bandwidth will lead to a 10 dB increase in the displayed signal. If, however, the noise is coherent (random impulse signals) the signal increases with the square of the bandwidth and a 10x increase in bandwidth leads to a 20 dB increase in signal. For example, if broadband data were taken with a bandwidth of 1 kHz and displayed as field strength per MHz, assuming broadband coherent noise, 60 dB would be added to the displayed signal. High noise from these thrusters is principally coherent but not purely so. There is another consideration. All MIL-STD 461 revisions require using instrument filters whose widths are defined 6 dB down from center (peak) transmission, but many instruments are configured with 3 dB filters. These 3 dB filters are broader than filters defined at the 6 dB level by a factor of approximately 1.5 if the filters have similar standard band shapes. If data is taken using a 3 dB instrument, its bandwidths must be redefined to be in accordance with MIL-STD 461. This requires a reduction in the displayed data by an amount that depends on the character of the noise as discussed above. So comparison of data taken under different specifications depends on the character of the noise, bandwidths, bandwidth definitions, and even somewhat on band shapes. It is for these reasons what the 461E specifics specific bandwidths, bandwidth definitions and requires no bandwidth normalization.

Observations from these spectra include the following. For vertically polarized receiving antennas:
1) between 10 kHz and 200 MHz, broadband emission exceed MIL-STD 461E limits by 20 to 60 dBμV/m for all flow rates and discharge voltages;
2) near 300 MHz, emission was 5 -10 dBμV/m above MIL-STD 461E limits;
3) emission decreased with increasing anode flow rate below 500 kHz and between 15 and 30 MHz but emission increased with flow rate between 1 and 5 MHz;
4) above 30 MHz there was no variation of emission with anode flow rate except at the 300 V discharge voltage which had higher emission at the highest flow rate obtainable (0.94 mg/s) at that voltage;
5) the emission variation with discharge voltage was less pronounced: below 500 kHz, emission from the thruster operating at the lowest voltage discharge (225

Table 4.
Discharge Current Spectrum Analyzer Bandwidths

Frequency band	Resolution Bandwidth	Video Bandwidth
1 kHz – 11 kHz	100 Hz	3.3 Hz
10 kHz -110 kHz	1 kHz	33 Hz
100 kHz – 1.1 MHz	10 kHz	330 Hz
1 MHz – 11 MHz	100 kHz	3.3 kHz
10 MHz – 110 MHz	1 MHz	33 kHz

V) was about 10 dBμV/m below that when the thruster was operating at the highest voltage (300 V);
6) there was no significant variation of emission with discharge voltage above 500 kHz;
7) emission decreased with increasing cathode flow rate below 500 kHz with a maximum variation of 10 dBμV/m;
8) between 500 kHz and 30 MHz there was no significant variation in emission with cathode flow rate;
9) there was no significant difference between spectra taken with the low pass filter inside the RFI box next to the thruster and spectra taken with the filter outside the vacuum chamber.

For horizontally polarized receiving antennas:
1) from 30 to 350 MHz broadband emission exceed MIL-STD 461E limits by 5 to 50 dBμV/m for all flow rates and discharge voltages;
2) between 30 and 200 MHz, there was no significant variation in emissions with anode flow rate;
3) between 200 and 350 MHz, emission was 5-10 dBμV/m lower for 0.80 mg/s anode flow rate than for the higher flow rates for all discharge voltages;
4) between 2 - 4 GHz for a discharge voltage of 300 V, emission was approximately10 dBμV/m higher for the 0.90 mg/s anode flow rate than the other two flow rate.

Discharge Current Oscillations

When the discharge filter was moved from the RFI box to a position outside the vacuum chamber, the discharge current oscillations for four different cathode flow rates were measured. Discharge current oscillations of Hall thrusters are often linked to their radiated emissions.

A Tektronics A6302 clip-on current probe with a 50 MHz bandwidth was attached to an exposed section of the anode cable. The signal from the current probe was fed to a Tektronics AM503B preamplifier connected to a Tektronix 2755AP spectrum analyzer through an RC high pass filter with a cutoff frequency of 530 Hz. Prior to taking these measurements, the probe was calibrated in-house between 30 Hz and 10 MHz. The measured transfer impedance was 3.3V/A and found to be independent of frequency.

For each thruster operating point the signal was sampled in one-decade frequency increments. A LabView program loaded spectrum analyzer settings for each frequency band and then stored the one thousand data points. After all spectral segments were collected, the cathode flow rate was varied and the measurements repeated. The resolution bandwidth in each band was chosen automatically by the spectrum analyzer. These settings were identical for all of the test runs and are summarized in Table 4. The spectrum analyzer's video bandwidth was used to reduce the noise without changing the envelope of the spectrum. The video bandwidths used are also listed in Table 4.

The data were post-processed by normalizing the measured signal by the corresponding resolution bandwidth and then correcting for the probe impedance. The graphs of the data are presented in Figure 20 and represent dBmA per unit resolution bandwidth. These were obtained with the thruster operating at 200 W (250 V, 0.8 A discharge current). A peak of -15 dBmA/Hz occurred near 20 kHz and decreased about 5% as the cathode flow rate increased from 6 to 12 % of the anode flow rate. No significant changes were observed in the spectrum as the cathode mass flow was varied. These spectra of the anode current are similar to the radiated spectra.

Summary

Electromagnetic emissions from Hall thrusters are linked to plasma instabilities and are not a strong function of the power of the thruster. For the BHT-200, as is typical of most Hall thrusters, the emissions between 10 kHz and a few hundred MHz greatly exceed MIL-STD 461E limits. In general, the more stable is the anode current, the lower the radiated emission, which is clear from the data presented here for the BHT-200. It is not uncommon for Hall thrusters to exhibit emissions above 461E limits at much higher frequencies (> 500 MHz). These higher frequency emissions usually occur in isolated bands and can be troublesome for some communication bands. The BHT-200 exhibited no emissions above 461E limits above 350 MHz at its anticipated operating point.

Acknowledgements

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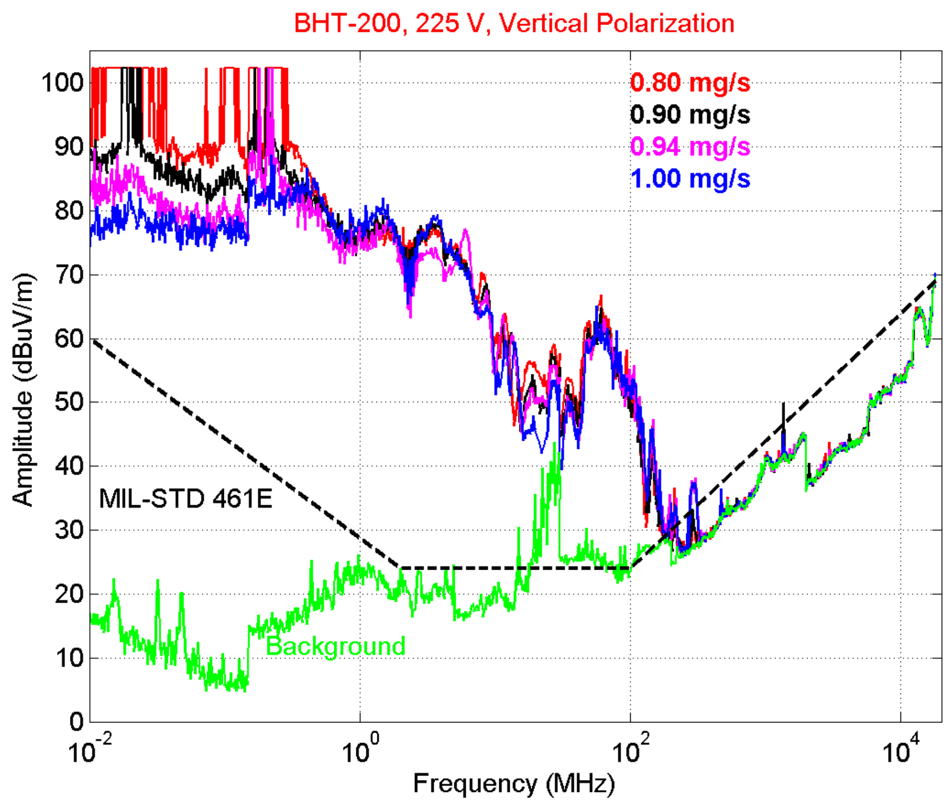

Figure 4. BHT-200 radiation at 225 V and four anode flow rates, vertical polarization.

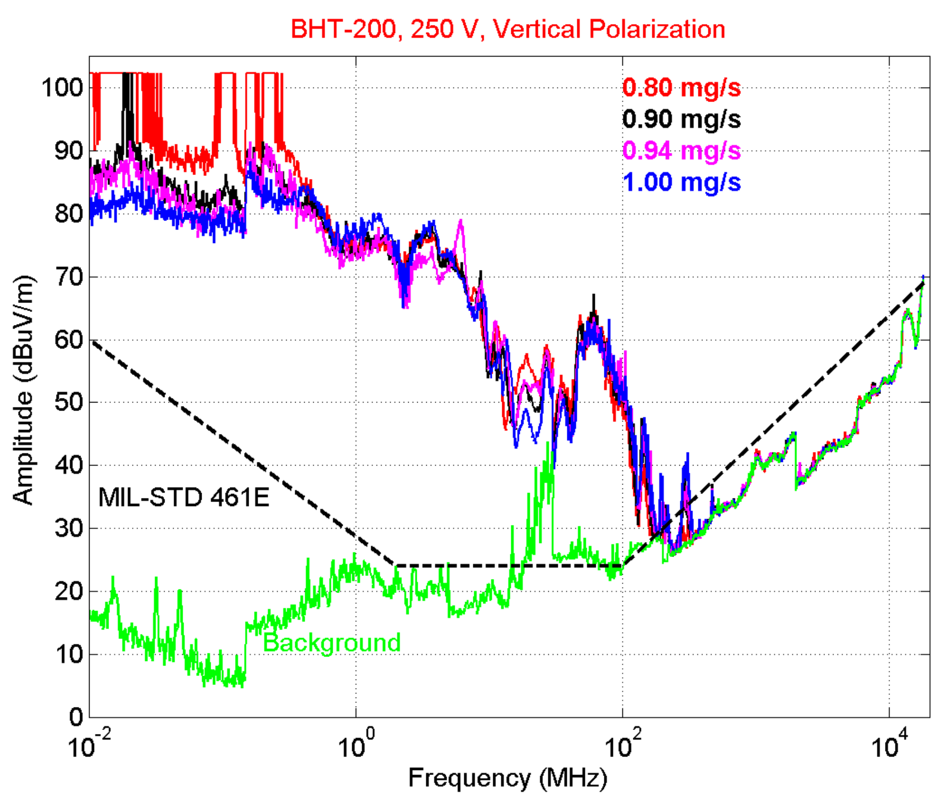

Figure 5. BHT-200 radiation at 250 V and anode flow rates, vertical polarization.

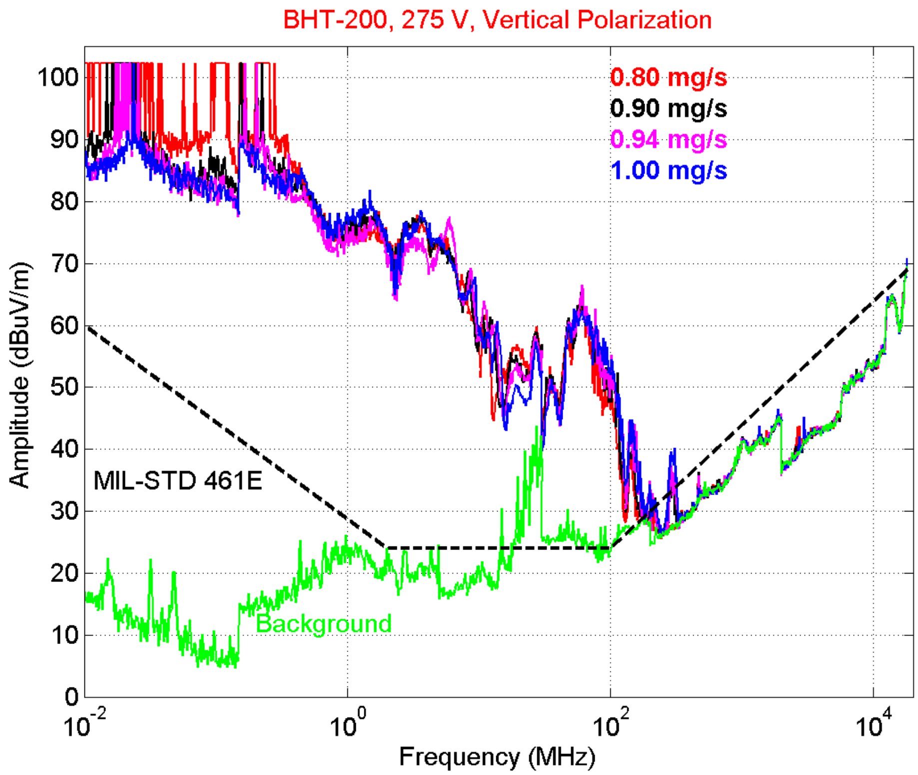

Figure 6. BHT-200 radiation at 275 V and four anode flow rates, vertical polarization.

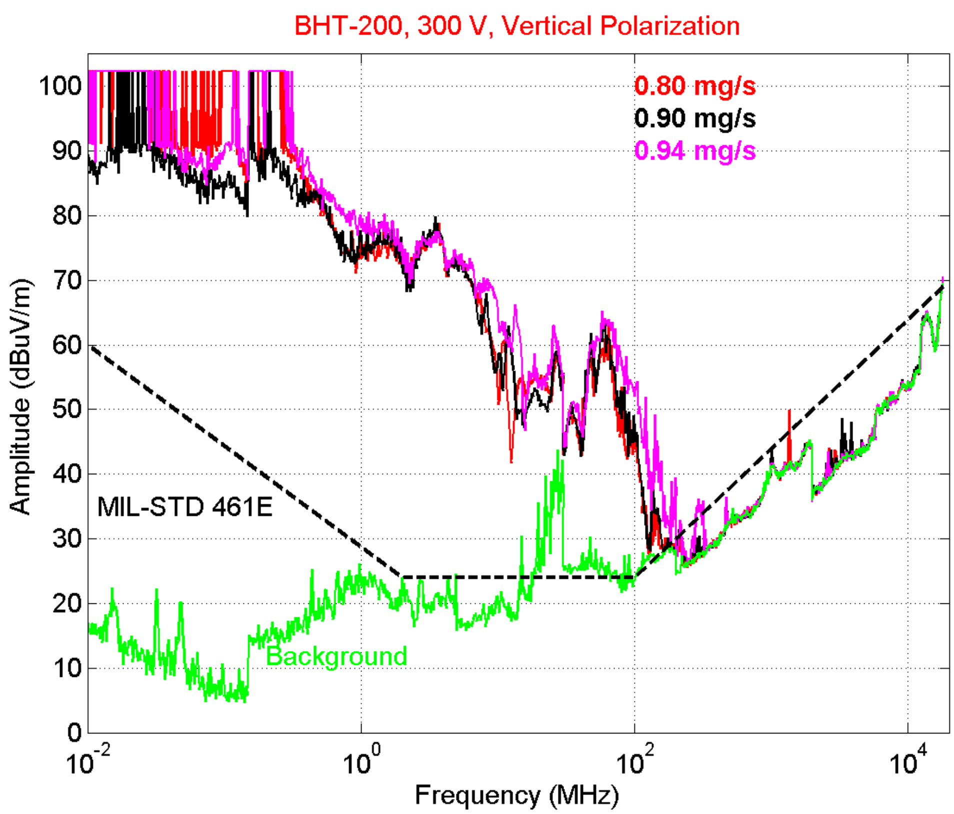

Figure 7. BHT-200 radiation at 300 V and four anode flow rates, vertical polarization.

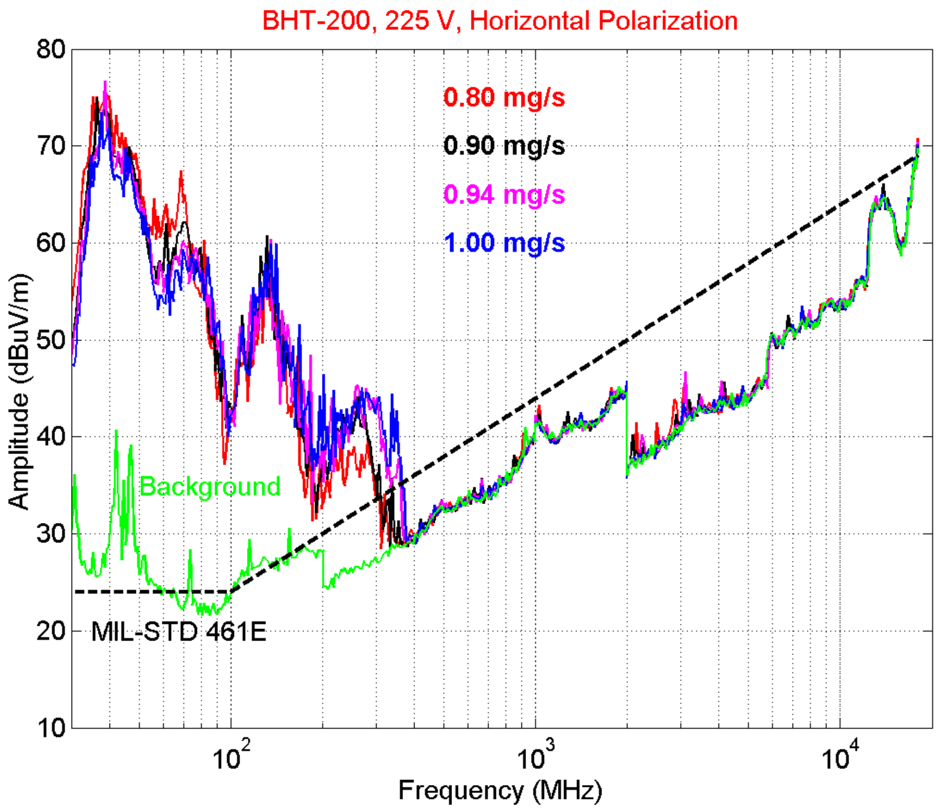

Figure 8. BHT-200 radiation at 225 V and four anode flow rates, horizontal polarization.

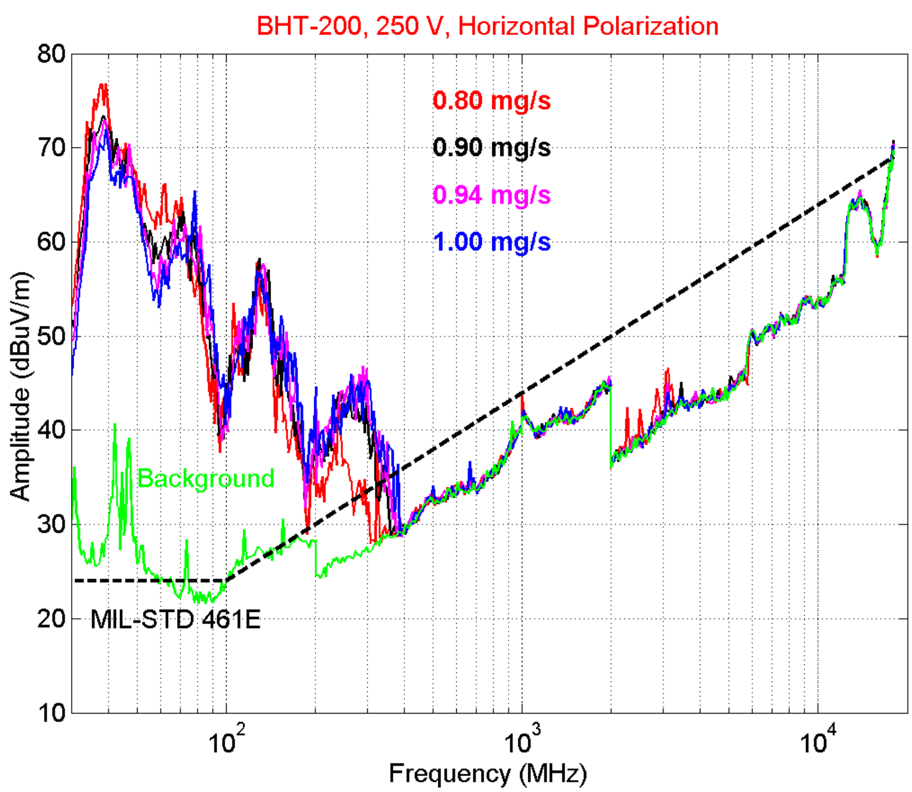

Figure 9. BHT-200 radiation at 250 V and four anode flow rates, horizontal polarization.

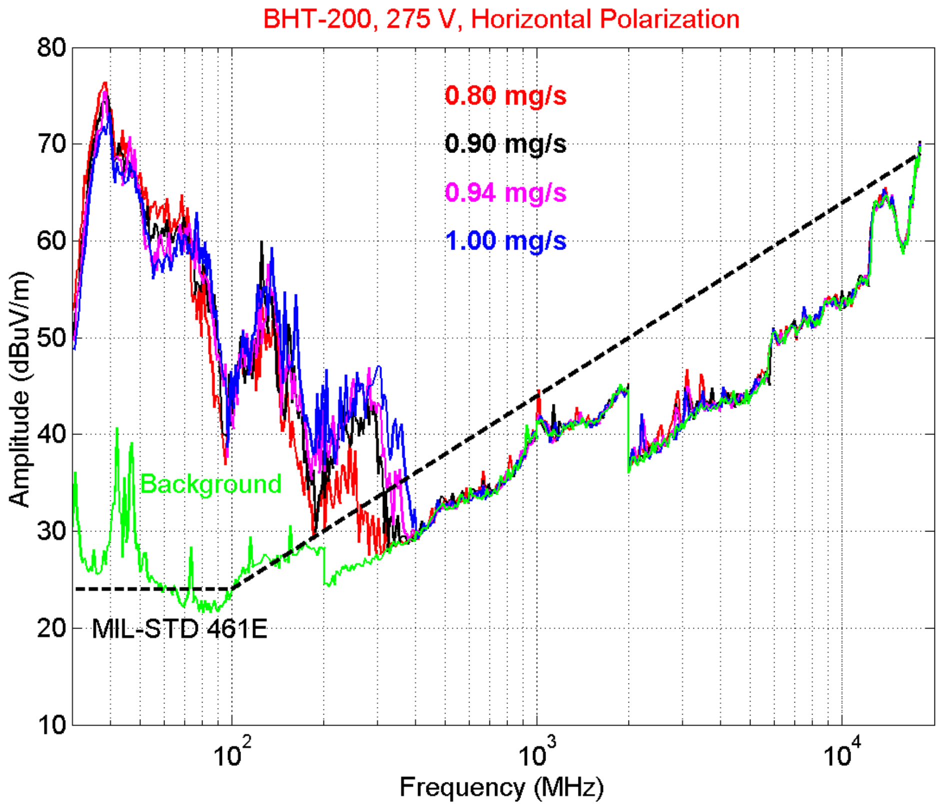

Figure 10. BHT-200 radiation at 275 V and four anode flow rates, horizontal polarization.

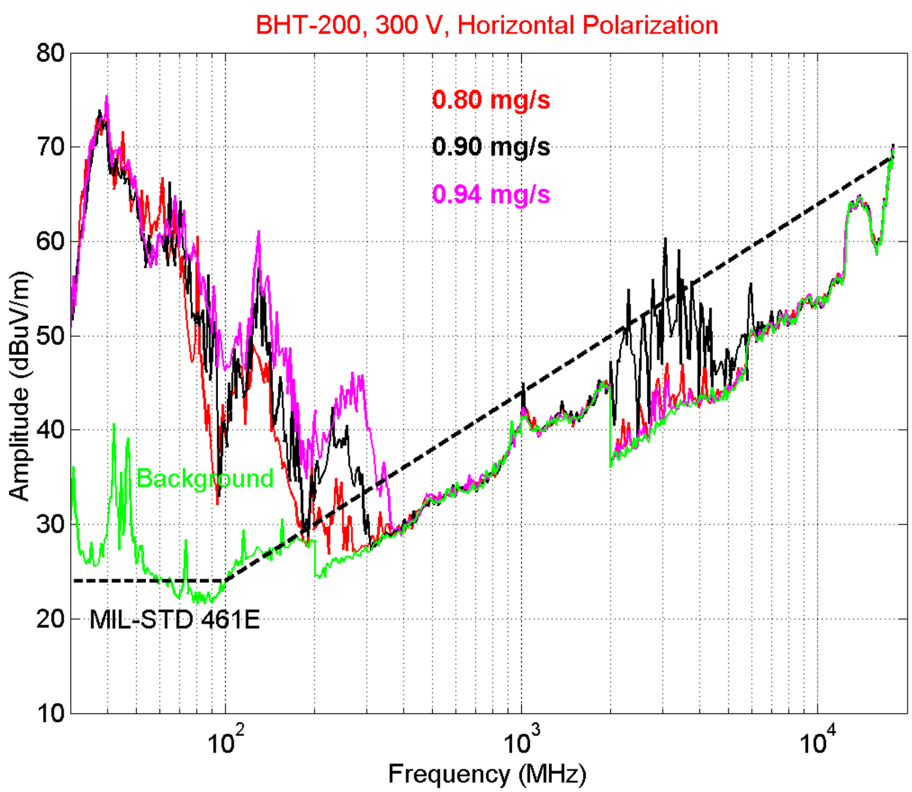

Figure 11. BHT-200 radiation at 300 V and four anode flow rates, horizontal polarization.

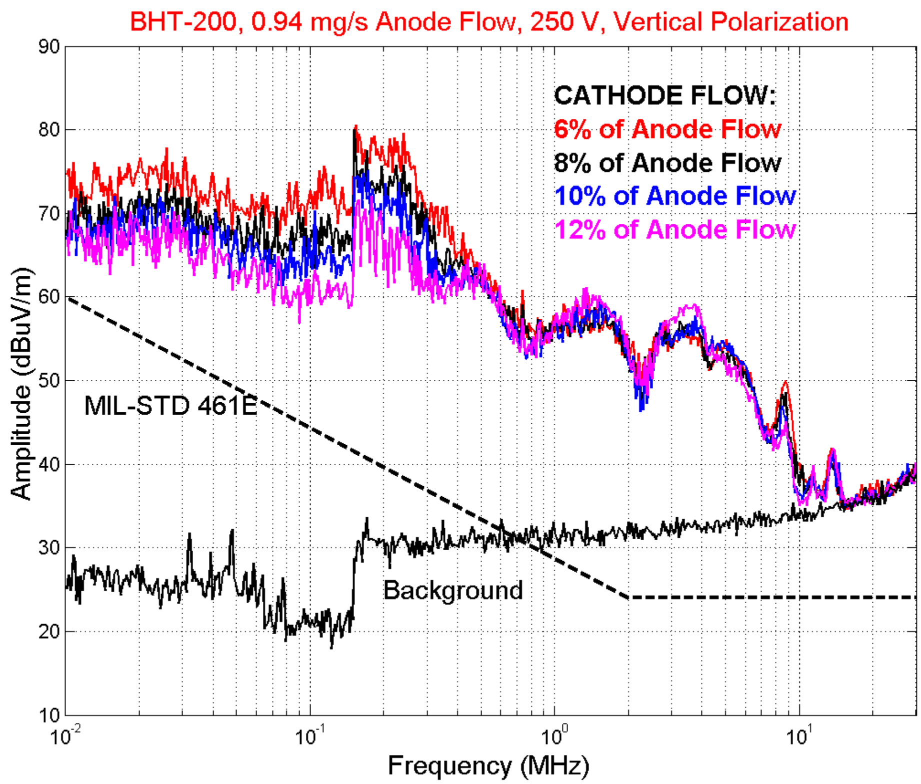

Figure 12. BHT-200 radiation at 250 V and four cathode flow rates, vertical polarization.

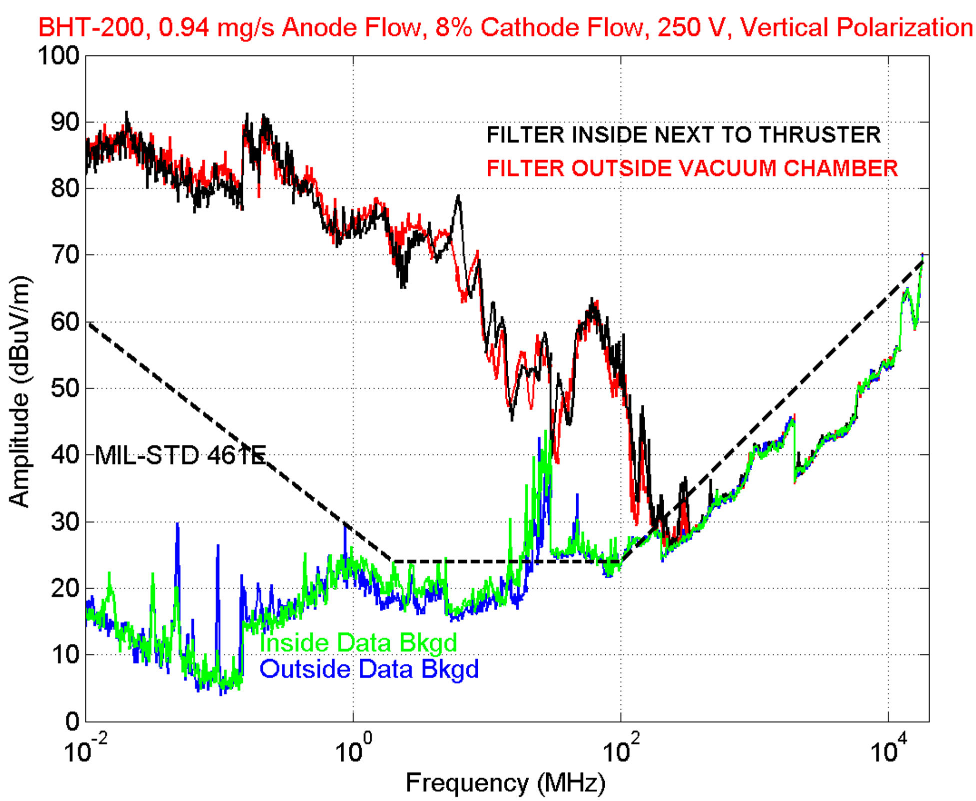

Figure 13. BHT-200 radiation at 250 V for two filter positions, vertical polarization.

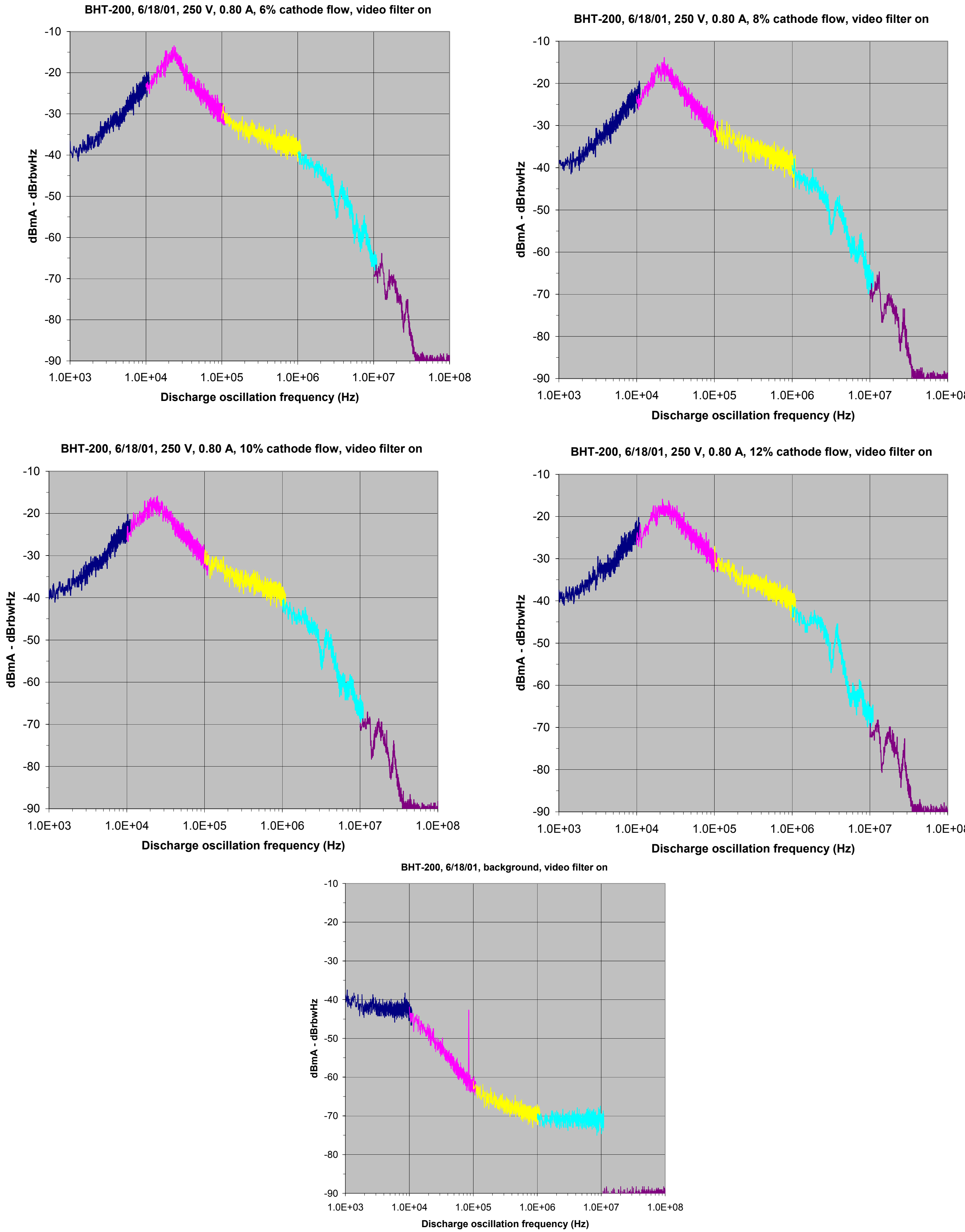

Figure 20. Spectra of BHT-200 current oscillations for four cathode flows. Bottom plot is power off background.