Hall Thruster Discharge Wall Erosion as a Function of Operating Condition and Background Pressure

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Abstract: Relative erosion rate of the boron nitride (BN) acceleration channel wall rings on the High Voltage Hall Accelerator (HiVHAc) at NASA Glenn Research Center was measured as a function of thruster operating condition and facility background. Optical emission spectroscopy was used to measure emission intensity of neutral boron, neutral xenon and ionized xenon, and neutral boron relative emission intensity are correlated with relative erosion rate. Emission intensities are also compared with ion current collected via Faraday Probe. Results show that as thruster input power increases, the relative erosion rate of the BN rings increases for a fixed discharge voltage. However, for a fixed input power, discharge voltage does not play a significant role in BN erosion rate in HiVHAc. From the limited data obtained in this experiment, erosion rate does not appear to have a significant relationship with facility background pressure.

Nomenclature

B	=	neutral boron species
c	=	speed of light
e	=	electron species
h	=	Planck's constant
I	=	emission intensity
I_i	=	emission intensity of species i
k	=	Boltzmann's constant
k_e^i	=	electronic excitation coefficients of species i
n_i	=	number density of species i
R	=	line intensity ratio
T	=	temperature
Xe	=	neutral xenon species
Xe^+	=	ionized xenon species
λ	=	wavelength

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I. Introduction

EROSION of the Boron Nitride acceleration channel wall rings (BN rings) is one of the main failure mechanisms in Hall Effect Thrusters (HETs). The most common method for measuring erosion of the BN rings is to perform lifetime testing of the thruster and comparing the physical profile of the BN rings before and after testing. This requires long-duration life testing in a high capacity vacuum facility. These facilities are expensive to operate due to the high power requirements, required liquid nitrogen cooling for pump operation, and the xenon propellant used to operate the thrusters for life tests. Furthermore, lifetime testing of thrusters cannot be interrupted, so the vacuum facility is in use for the entire testing timeframe, and no other experiments can be performed in the facility. This method for measuring erosion does not easily allow for the determination of BN ring erosion as a function of thruster operating condition. In order to accumulate an amount of erosion measureable by physical profilometry, the thruster requires operation for hundreds to thousands of hours. Then, the thruster is removed from the vacuum facility so that the profile of the BN rings can be measured. In order to determine how thruster operating condition affects erosion, this procedure must be repeated for multiple operating conditions. This method of testing is cost and time prohibitive. Cavity ring down spectroscopy (CRDS) is another method for measuring erosion rate in HETs as a function of operating condition.[1–3] CRDS requires expensive equipment, and an intricate laser setup, which prevent it from being utilized widespread or easily transportable. Additionally, the complex setup inside the vacuum facility requires that the only active experiment be CRDS. As such, there are no complete measurements of how thruster operating condition, magnetic topography, facility background pressure, and discharge oscillations affect acceleration wall erosion.

Recently, an in situ diagnostic method was developed for measuring the relative erosion of a Boron Nitrite (BN) sample located downstream of a Kauffman-style ion source as a function of ion source operating condition. The experiment showed that the emission intensity of neutral boron (B I) measured using optical emission spectroscopy (OES) is correlated with the amount of erosion, and therefore, the erosion rate of the BN.[5] This diagnostic method has been applied to the High Voltage Hall Accelerator (HiVHAc) at NASA Glenn Research Center to determine the relative erosion rate of the BN acceleration channel wall as a function of thruster operating condition and vacuum chamber background pressure. The experiments for this study were performed while other experiments occurred on HiVHAc. Furthermore, uninterrupted operation or extended operating time of HiVHAc was not required.

II. Background

There have been a large number of studies to relate the radiation emission intensity of neutral Boron in the plasma plume to the erosion rates of the acceleration channel walls of HETs. Pagnon et al. demonstrated this process in a variety of experiments, and they proposed a method for relating the density of boron in the plasma plume to the densities and emission intensities of neutral xenon and ionized xenon via Eq. 1 and Eq. 2. This method is based on assumptions of the coronal model[6] and actinometry, and the authors performed some measurements of erosion as a function of HET operation condition.[7–9]

$$R = \frac{I_{B(250\,nm)} \times I_{Xe(828\,nm)}}{I_{Xe^{+}(484\,nm)}} \propto n_B \tag{1}$$

$$\frac{I_{B(250\,nm)} \times I_{Xe(828\,nm)}}{I_{Xe^{+}(484\,nm)}} \propto \frac{n_B n_e k_e^{B} \times n_{Xe} n_e k_e^{Xe}}{n_{Xe} n_e^{Xe^{+}} k_e^{Xe^{+}m}} \tag{2}$$

Dyshlyuk and Gorshkov measured the emission intensity as a function of magnetic field topology with a method that is more applicable for a thruster with anode layer (TAL) type HET.[10] They also correlated the erosion rate with measured erosion volume from the same HET. This could present issues because the erosion rate may have changed with time and geometry of the acceleration channel walls. Hargus and Strafaccia used vacuum ultraviolet emission of neutral boron sputtered from a 200 W HET as a function of magnetic field strength, discharge potential, and propellant flow rate,[11] and Williams et al. presented results of emission intensity as a function of thruster operating condition. Neither of these studies correlated emission intensity with physically measured erosion amounts and rates.[12,13]

The greatest challenge to these types of studies is the extent to which emission intensity can be quantifiably converted to erosion rate. This is because emission intensity is a relative measurement dependent on the spectrometer, sensor, OES diffraction grating, OES slit width, light path, lens count, etc. Without a complicated calibration procedure that is valid for only a single wavelength, emission intensity measured using OES will remain a relative value. When the calibration is performed, the measured emission intensity of B I is only an indication of the amount of boron that has been elevated to the excited state at a specific wavelength rather than a direct measurement of how much BN has been removed from the discharge channel. This causes uncertainty with regards to thruster operating condition. For example, when the plasma is more energetic at a thruster operating condition, more emission at the excited B I wavelength may be observed than at a lower energy operating condition. This can be caused by the presence of more erosion or more B I being elevated to the excited state. Another uncertainty occurs due to the fact that emission signals are integrated over the collection volume. This limits the spatial resolution of the diagnostic and allows for detection of the same particle more than once. Another significant challenge for OES erosion measurements is the fact that there are several other emission lines from materials that can be found in HET plumes within the same wavelength range as those of neutral boron.[14] Therefore, care must be taken to ensure any line integration does not include those emission intensities.

A recent study demonstrated that the erosion rate of BN can be qualitatively related to emission intensity of B I, and ion density and energy in a plasma plume.[5] The study found that as the ion energy of the plasma increased, the measured relative emission intensity of B I increased. As previously mentioned, this could be caused by more erosion, or more excitation of the eroded BN. Profilometry measurements showed that the increased emission of B I did result in more erosion occurring. Thus, if the erosion rate at one operating condition of an HET is known, then using OES, the erosion rates at other operating conditions can be determined. This study correlated erosion amount with relative emission intensity for known ion energies and densities where plasma impinged a BN sample. It also showed that with a proper OES system, neutral boron emission can be separated from other sources of emission.

III. Experimental Setup

All experiments were conducted at NASA Glenn Research Center (GRC) in Vacuum Facility 12 (VF-12). Radiation emission intensity was measured on the BN rings of the HiVHAc Hall thruster, and a Faraday probe was mounted downstream. Figure 1 shows the experimental setup within VF-12. HiVHAc operates over an input power range between 0.3 and 3.5 kW, with specific impulses between 1,000 and 2,000 seconds.[15] Data were collected for a variety of thruster operating conditions and facility background pressures, shown in Table 1. Facility background pressure was controlled via a neutral background flow of xenon into VF-12. There were two ion gauges to measure background pressure in the facility during the experiments. One was attached to the facility wall via vacuum feedthrough, and another was directly beneath the thrust stand on which HiVHAc was mounted. The ion gauge was flush with the HiVHAc exit. Manufacturer specifications indicate an accuracy of the ion gauges to 6% of the measured reading.

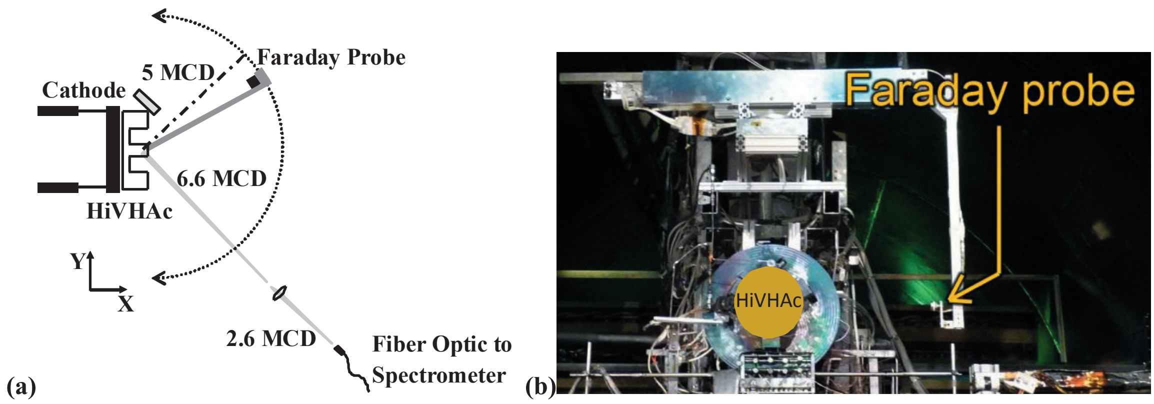

Figure 1. Experimental Setup. *Experiments took place in VF-12 at NASA GRC. Faraday probe was located 5 mean channel diameter (MCD) downstream of HiVHAc. Fiber optic was covered by a shield to protect from material deposition when OES was idle.* **(a)** *schematic of the experimental setup, and* **(b)** *photograph of HiVHAc with Faraday probe*

Table 1. Thruster operating conditions

Set Point	Power (kW)	Discharge (V)	Discharge (A)	Inner/Outer magnet current (A)	Anode MFR† (sccm)	Cathode MFR* (sccm)	Chamber Pressure (torr)
1*	1.023	300	3.41	3.44	38.9	4.5	1.10E-5
2*	2.034	300	6.78	4.1	72.4	4.5	1.83E-5
3	2.031	300	6.77	4.1	70.4	4.5	3.65E-5
4	2.04	300	6.8	4.1	70.4	4.5	7.33E-5
5*	0.995	500	1.99	4.1	24.0	4.5	7.55E-6
6	1.985	500	3.97	4.1	43.8	4.5	1.24E-5
7*	2.0	500	4.00	3.5	43.8	4.5	1.23E-5
8	1.98	500	3.96	4.1	42.8	4.5	3.65E-5
9	3.53	649	5.43	4.1	53.8	4.5	1.43E-5
10	3.55	649.6	5.47	3.0	53.8	4.5	1.46E-5

*Faraday probe data are available †MFR = Mass flow rate

A. Optical Emission Spectroscopy System

A state-of-the art spectrograph (IsoPlane from Princeton Instruments) and CCD camera (Pixis from Princeton Instruments) were used to perform OES measurements on HiVHAc at a variety of operating conditions. A previous study proved that the OES system is capable of differentiating between the ionized iron (Fe II) emission lines that are very near the neutral boron (B I) emission lines at 249.677 nm and 249.772 nm. It was shown that the Fe II emission intensity is relatively low compared with that from BI. Additionally, while the 249.772 nm line of BI may be impacted by the presence of the Fe II line at 249.771 nm, the 249.677 nm line of B I is not impacted by any of the Fe II lines.[5,16]

The spectrograph and CCD camera work together to measure intensity vs. wavelength data for a variety of wavelength sets associated with each emission line shown in Table 2 for each operating condition of HiVHAc from Table 1. For each wavelength set, a corresponding diffraction grating was used based on the required center wavelength. The grating diffracts the light into several wavelengths traveling in different directions. The CCD camera then measures the intensity of the light as a function of location on the sensor. The higher the groove density on the grating, the more the light is diffracted. Therefore, as the groove density on the grating increases, the resolution of the spectrograph increases, but the relative intensity of the light for a given wavelength decreases. Therefore, an intensity calibration is required.

Table 2. Wavelengths measured using OES, the source of emission, and OES system settings

Spectrum	Abbreviation	Wavelength(s), nm[16]	Source of emission	Center wavelength, nm & Grating, grooves/mm
Neutral boron	B I	249.68 249.77	HiVHAc acceleration channel wall rings	250 nm Ultraviolet (3600)
Neutral xenon	Xe I	823.16 828.01	HiVHAc propellant	830 nm Near UV to visible (1800)
Singly-ionized xenon	Xe II	484.43	HiVHAc propellant	485 nm Near UV to visible (1800)

A fiber optic cable designed for ultraviolet to visible wavelengths was used to transmit the light from the vacuum chamber to the spectrograph. Inside the vacuum chamber, a lens was used to focus the light into the fiber optic cable, and a fused silica glass shield was used to protect the lens from sputtered material within the vacuum chamber while allowing the transmission of ultraviolet light. The fiber optic cable was located 2.6 mean channel diameters (MCD) from the lens, which was 6.6 MCD from the BN surface of the inner acceleration channel wall. The diameter of the collection area on the BN was 0.13 MCD. During OES idle periods, a metal cover was in place over the optics to reduce any sputtered material deposition on the glass. The optics and fiber optic cables did not move throughout the experiment, so the effects of the lens-fiber-feedthrough system are the same for each operating condition. Since the goal of the study is to compare relative emission intensity with thruster operating condition, a transmission line calibration was not needed.

The spectrograph was wavelength calibrated using either a mercury lamp or an argon/neon lamp, depending upon the diffraction grating used, with known emission wavelengths. The OES system was relative intensity calibrated at the wavelengths of interest using a tungsten halogen lamp with an operating temperature of 3400 K as a blackbody radiation source with Planck's blackbody radiation equation (3).[17]

$$I = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{3}$$

Spectra from the tungsten lamp were collected using the same path lengths, spectrograph settings, and CCD camera settings as those used during emission collection on HiVHAc. A calibration factor relating the relative measured spectra of the tungsten lamp to the calculated relative intensity from Planck's blackbody radiation equation was calculated for each wavelength of interest in Table 2. The recorded relative emission intensity was multiplied by the corresponding calibration factor to give true relative intensity.

Error estimates on relative intensity are based on the standard deviation of the data. Intensity data were collected using software from the OES manufacturer, LightField. For each center wavelength the exposure lasted 10 ms, and 25 exposures were collected and averaged. Error estimates for emission intensities range from less than 1% for Xe I emission up to 12% for B I emission.

B. Faraday Probe

The BN erosion study was a secondary experiment. The primary experiment included a Faraday probe downstream of HiVHAc that measured ion current density and plume divergence. The Faraday probe was located 5.0 MCD from the thruster surface. Although not optimum, the Faraday probe provided ion current density with which to compare the emission intensity. Ideally, an energy analyzer would also have been used to determine the fraction of multiply charged ions; however, a correction factor based on previous HiVHAc experiments by Huang, et al. was used to estimate the actual beam current.[18] Uncertainties in Faraday probe analysis come from background charge exchange (CEX) and secondary electron emission (SEE) effects. For the analysis methods utilized by Huang, et al. uncertainty is no more than 2% for a full set of data collection.[18] Because a correction factor based on previous experiments was utilized, the uncertainty in the absolute Faraday probe measurements for this experiment should be considered higher. However, since the goal of the experiment is to compare operating conditions, the corrected data will give an acceptable indication of the ion density in a specific location of the plume for each operating condition.

IV. Results

Emission intensity data were collected during HiVHAc operation at a variety of thruster operating conditions and at multiple background pressures for a given operating condition. These results will compare relative erosion of the BN acceleration channel wall rings as a function of discharge voltage, input power, and background pressure.

A. Thruster Operating Condition

HiVHAc was operated at 3 power settings (1 kW, 2 kW, and 3.5 kW) at three discharge voltages (300 V, 500 V, and 650 V). All of the operating conditions had the same magnetic field settings with the exception of the 1 kW, 300 V throttle point, where the inner and outer coils operated at a lower current. These throttle points were operated with no additional background flow so that the chamber pressure would be at a minimum. Figure 2a – 2e, shows the corrected, relative emission intensity as a function of input power and discharge voltage for B I, Xe II, and Xe I, and Fig. 2f shows the corresponding ion current measured at 5.0 MCD. Error bars are shown on the B I and Faraday probe plots only because they are significant with respect to the plotted value.

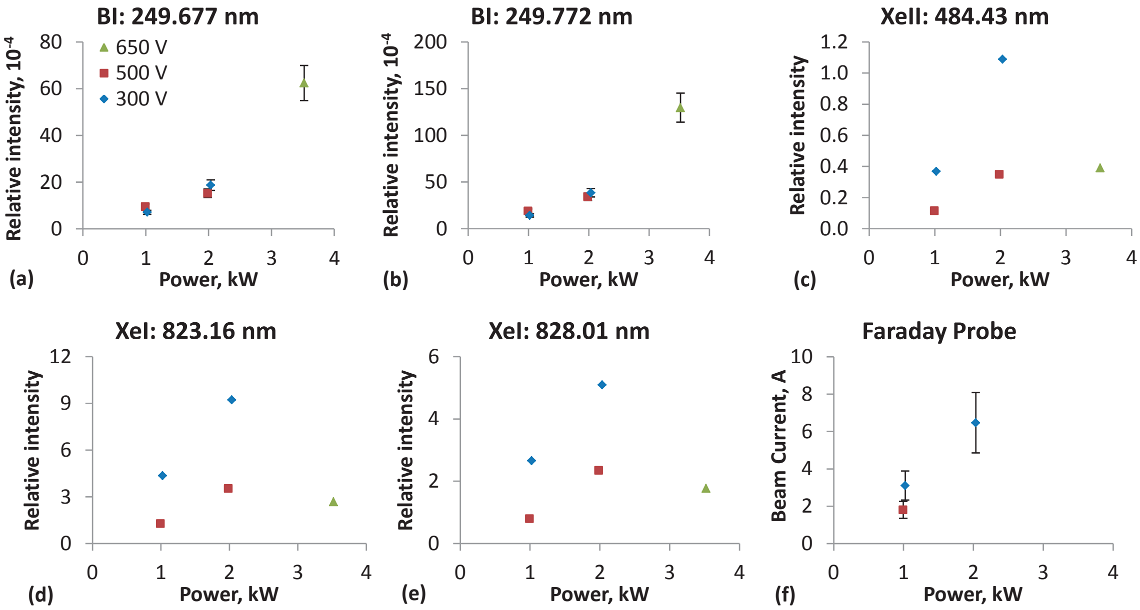

Figure 2. Emission intensity vs. thruster operating condition. *Corrected, relative emission intensity as a function of input power and discharge voltage for **(a)** neutral boron measured at 249.677 nm, **(b)** neutral boron measured at 249.772 nm, **(c)** ionized xenon measured at 484.43 nm, **(d)** neutral xenon measured at 823.16 nm, and **(e)** neutral xenon measured at 828.01 nm. Ion beam current for the corresponding operating conditions are shown in **(f)** where available. Error bars are only shown on (a), (b), and (f) because they are significant with respect to the plotted value for those data only.*

As input power increases for a given discharge voltage, the relative intensity of neutral boron increases; therefore, according to previous work the relative erosion rate increases.[5] This is expected because the ion density in the plume increases as indicated by the increased emission intensity of Xe II and increased beam current. The anode flow rate is also increasing to achieve the higher power condition. For a set input power, there does not seem to be any correlation in the emission intensity of neutral boron with the discharge voltage, and therefore no correlation in the erosion rate. However, emission intensities of neutral xenon and ionized xenon increase with decreasing discharge voltage (increasing discharge current and anode flow rate). This makes sense because although there is more neutral and ionized xenon in the plume, the energy levels may not be high enough to sustain the excitation to cause erosion due to the lower discharge voltage.

B. Background Pressure

HiVHAc was operated at varying facility background pressures at 2.0 kW input power for two discharge voltages (300 V, and 500 V). All of the operating conditions had the same magnetic field settings with the exception of the 500 V, low pressure condition, where the inner and outer coils operated at a lower current. Figure 3a – 3e, show the corrected, relative emission intensity as a function of background pressure and discharge voltage for BI, Xe II, and Xe I. Error bars are shown on the BI plots only because they are significant with respect to the plotted value.

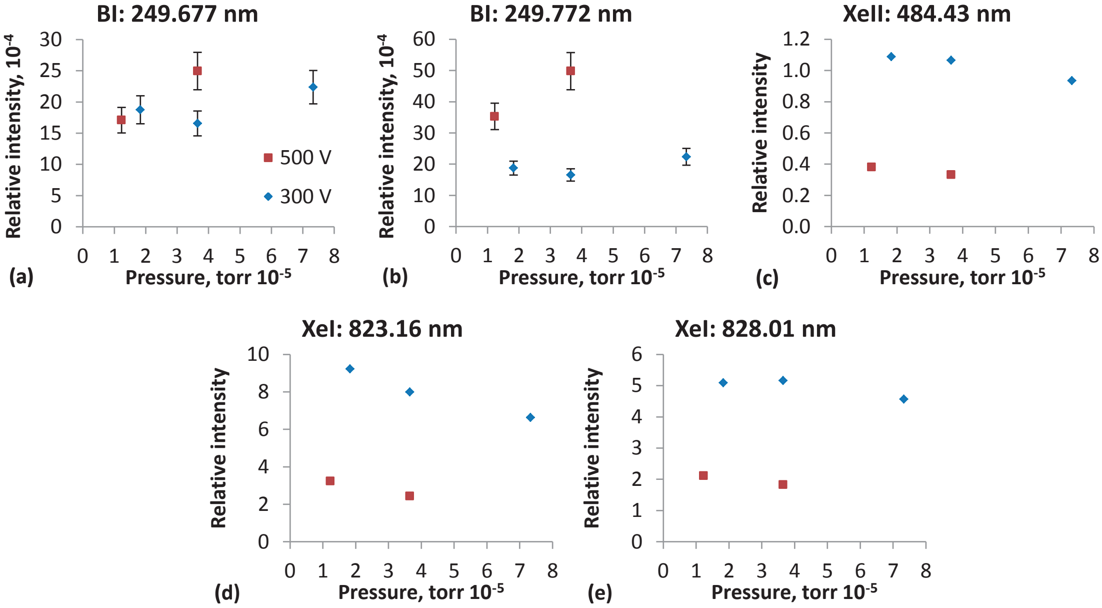

Figure 3. Emission intensity vs. background pressure. *Corrected, relative emission intensity as a function of background pressure and discharge voltage with HiVHAc operating at 2 kW for* ***(a)*** *neutral boron measured at 249.677 nm,* ***(b)*** *neutral boron measured at 249.772 nm,* ***(c)*** *ionized xenon measured at 484.43 nm,* ***(d)*** *neutral xenon measured at 823.16 nm, and* ***(e)*** *neutral xenon measured at 828.01 nm. Error bars are only shown on (a) and (b) because they are significant with respect to the plotted value for those data only.*

Emission intensity of neutral boron appears to increase as the facility background pressure increases. However, due to the limited data, no conclusions can be made regarding the relative erosion rate as a function of facility background pressure. Further experiments are necessary to determine if facility background pressure plays a role in the erosion rate of Hall thrusters. Emission intensity of excited neutral xenon and ionized xenon decreases as background pressure increases. This is expected since there will be more cold neutral xenon particles in the vacuum chamber with which the excited xenon can collide.

V. Conclusion & Future Work

It has been shown that OES can be used to determine the relative erosion rate of the BN acceleration channel wall rings as a function of HiVHAc operating condition. Higher power settings result in higher erosion rates of the acceleration channel walls at a set discharge voltage. For a set input power, the limited operating conditions from this work resulted in no apparent correlation between discharge voltage and relative erosion rate. Additional OES measurements when the facility background pressure was varied for 2 kW of input power at two discharge voltages were similarly inconclusive. These results indicate that further experiments with more numerous operating conditions would be beneficial for further data correlation. Future work should include a dedicated experiment to measure relative emission intensity using the OES system described in this work to determine relative erosion rates as a function of a wide variety of HET operating conditions, magnetic field topographies, and facility background pressures. A Langmuir probe and an energy analyzer should be used to determine ion number density, electron temperature, ion charge state, and ion energy. Investigation of an HET that has the capability to operate with and without magnetic shielding topologies would be beneficial to determine whether magnetic shielding is eliminating erosion, limiting erosion to rates that are less than back sputter rates, or shifting the erosion to another region of the thruster.

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