# FURTHER INVESTIGATIONS OF AN OPEN DRIFT HALL THRUSTER WITH BORON NITRIDE AND DIAMOND WALL

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## ABSTRACT

The operating characteristics of a linear-geometry (open electron drift) Hall thruster are revisited under cryogenically pumped vacuum conditions. A comparison is made between cases in which the thruster is operated with channel walls fabricated from plate diamond, and from boron nitride. These studies reveal a new operating regime/mode that exists at high magnetic field conditions that has never been reported for Hall thrusters, seen only when operating with diamond as the channel wall material. Operating regimes comparable to those seen in co-axial discharges are investigated using streak photography. The reason for this pulsed, low mean current regime is not yet understood but we conjecture that it is due to the difference between the secondary electron emission characteristics of boron nitride and diamond.

## I. INTRODUCTION

Modern day operational Hall thrusters are closed electron-drift magnetized discharges, with uninterrupted Hall current [1]. In recent years, however, we have shown [2,3] that the requirement to close the electron drift is not an absolute one, and that an open electron drift thruster will work, in principle, if there is a mechanism for the electron transport across the magnetic field (either through wall collisions or "virtual" collisions with fluctuating electric fields) during the electron's residence time within the acceleration zone. In past studies, we have measured the performance of such a thruster at low powers, and were surprised to see reasonable thrust efficiency, in the range of 15% at about 75 W [4]. While such thrust efficiency is small in comparison to thrusters that operate in the 200 – 1000 W range, it is comparable to that measured in co-axial thrusters of low power range.

It is noteworthy that the generally lower thrust efficiency, and the consequence of the scaling relations for Hall discharges to low powers results in a significant increase in the particle and energy flux to the ceramic (electrically insulating) walls of the discharge [5,6]. The performance of SPT (Stationary Plasma Thruster) – like thrusters is known to depend strongly on the dielectric wall material making up the discharge channel [7]. Understanding these wall effects and engineering channel wall materials for improved performance is critical to the development of low power Hall thruster technologies.

Two years ago, we presented initial results on a study of the behavior of a low-power linear-geometry Hall thruster that operated with polycrystalline diamond walls [8]. The linear, open-drift design was attractive for these studies because it allowed us to investigate performance on advanced ceramic materials that are not easily machined but are available in plate form. That study was prompted by a preceding study in our laboratory that indicated that diamond was significantly better than both boron nitride and silicon carbide in resisting sputter erosion to energetic xenon ions - a result consistent with prior available data in the published literature [9]. When integrated into a low-power linear geometry source, we found that the diamond resulted in a relatively low total discharge current in comparison to the case of a pure boron nitride channel, although slight differences in the injector geometry precluded a direct comparison. In both cases, *i.e.*, that of boron-nitride walls and diamond walls, the linear Hall thruster resulted in an ion beam profile that was highly asymmetric, with an anisotropic beam divergence of $15^o$ (in the direction of **B**) and $60^o$ (parallel to the **E**×**B** direction). Unlike the case with boron nitride walls, operation with the diamond walls was limited to 200V or higher, due to the emergence of large-scale fluctuations at lower voltages. The limitations in voltage when operating with diamond walls motivated further study. In this paper, we present new results of studies aimed at understanding the differences in operating conditions of this linear-geometry thruster when instrumented with either diamond or boron nitride walls. In particular, we have carried out experiments in a vacuum chamber that is pumped cryogenically (in Ref. 8, the vacuum conditions were obtained with diffusion pumps operating without baffles). The interpretation of the operating characteristics presented previously [8] was limited because of the possible contamination of the insulators with silicon residue from the cracking of pump oil. Also, we have taken fully time-resolved streak images of the discharge, with spatial resolution either perpendicular, or parallel to the **E**×**B** direction. As seen below, qualitative analysis of these images clearly reveal the characteristic breathing mode instability, as commonly seen in co-axial discharges, and further reveal, for the first time, the existence of fine structure to the instabilities, of scale lengths less than the channel width.

## II. EXPERIMENTS

### II.1. Thruster

The details of the linear Hall thruster operated here are described in previous papers [3-5,8]. This thruster incorporates design improvements to allow stable operation at high voltage. The discharge and the experimental set-up, along with the coordinate system used in this paper, are shown to the left in Fig. 1. The magnetic circuit was built from cast gray iron and consisted of two rectangular solenoid coils, two front pole pieces, and one back pole piece. A magnetic screen was also used to sharpen the magnetic field profile. The circuit is capable of a peak magnetic field strength of 1500 Gauss at 3 A of coil current; however, the coil current was kept below 1 A under vacuum to prevent melting of the kapton wire insulation. The magnetic field profile in the axial (*z*) direction for the nominal operating coil current of 1 A is shown to the right in Fig. 1. The peak field for this condition is approximately 800 Gauss, and the field strength at the anode is over 100 Gauss. The field had excellent uniformity (< 1 % variation) along the *x* direction.

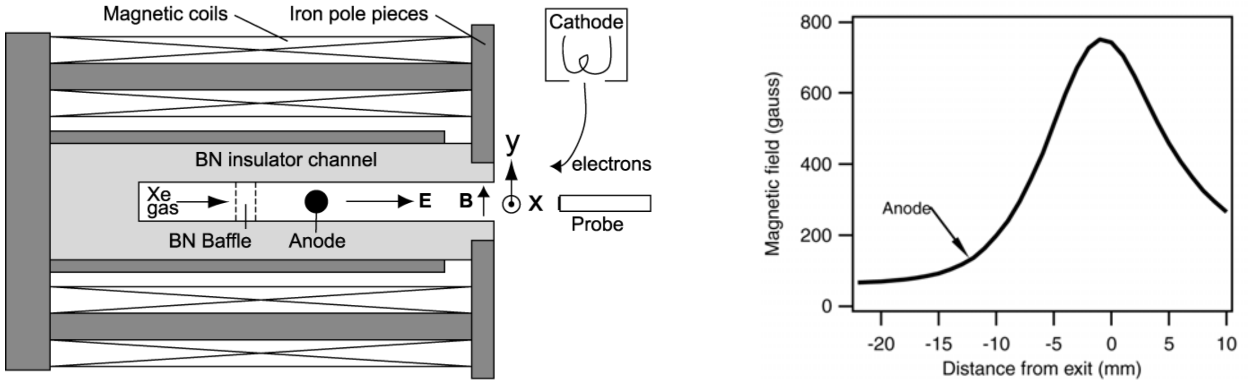


Fig. 1. Left: Linear Hall thruster design details. Right: Magnetic field profile.

The channel of this thruster was constructed to allow testing of different wall materials. The supporting channel structure was made of boron nitride, and was machined with two pockets that allow rectangular plates of different wall materials to be clamped into place, as shown in Fig. 2 (with diamond plates inserted).

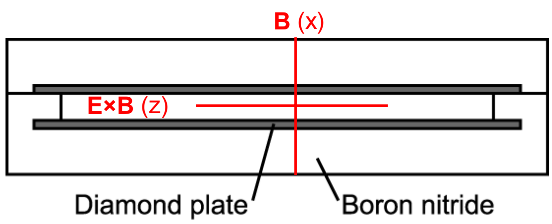


Fig. 2. Schematic of diamond channel design. The red crossbars represent the image of the entrance slit of the streak camera, for the streak images described in the text.

For the diamond thruster, we used 1 mm thick plates of pure CVD diamond provided by *sp*$^3$ Inc. [10]. The surfaces facing the plasma were polished to a mirror finish. For the comparison case, we used boron nitride plates of the same geometry as the diamond plates. A boron-nitride baffle separates a plenum from the anode, a tungsten rod 1.6 mm in diameter. A commercial hollow cathode (Veeco/IonTech HCN-252) was used to neutralize the ion beam. The cathode was located 28 mm downstream of the channel exit, 45 mm from the channel in $y$ and centered in $x$. The thruster was generally operated with 0.6 mg/s of xenon through the anode and 0.3 mg/s of xenon through the cathode. Both the BN-channel and diamond-channel thrusters proved capable of continuous operation at voltages as high as 300 V.

### II.2. Vacuum Chamber

All experiments were performed in a stainless steel vacuum chamber pumped by a single, 22 in diameter cryogenic pump (CVI, Inc. Model TM-1200). The pump was capable of being isolated from the chamber by a 22 in gate valve. This pumping plant provided an operating pressure of $10^{-4}$ torr at the nominal operating conditions, as measured by an ionization gauge uncorrected for xenon. Separate DC power supplies powered the anode, cathode heater, cathode keeper, and magnet coils. The cathode body was kept at tank (ground) potential. The discharge voltage and current were monitored with digital multimeters. Discharge current oscillations were measured with a powered differential amplifier (Tektronix P5200) placed across a 4 Ω series resistor and recorded by a high-speed PC-based digital oscilloscope (National Instruments PCI-5102).

### II.3. Streak Camera

A preliminary characterization of instabilities in the linear Hall thruster plasma was carried out with a Hamamatsu C2830 Streak Camera, which allows transient visible phenomena to be captured in an image with one space and one time dimension. A streak camera sacrifices one space dimension to provide a record of a line of light changing with time. This is accomplished by focusing an image on a narrow adjustable slit (see red marker on Fig. 2, which represents, qualitatively, the location of slit, imaged back onto the discharge channel and plasma). The light passing through the slit strikes a photocathode, converting the signal into a stream of electrons. These electrons pass between a pair of high voltage plates that sweep the signal across a phosphor screen after being amplified by a micro-channel plate. The sweep speed can be adjusted from 10ns to 1ms. A CCD camera records the visible image on the phosphor screen. In the results presented below, emission was collected, without spectral discrimination in order to maximize signal, as it was observed that the use of interference filters centered about particular xenon transition wavelengths resulted in signals that were too low to be detected at the shortest sweep durations investigated (~10 μs).

## III. RESULTS AND DISCUSSION

### III.1 I-V Characteristics and Discharge Oscillations

Discharge current-voltage (I-V) curves are compared in Fig. 3, for the two wall materials, with the magnet current set at 1 A, and for the case of diamond walls, with a magnetic current of 0.5 A, corresponding to a peak magnetic field of about 400 Gauss. The figure displays the mean current, with the mass flow through the anode set at 0.6 mg/s. For a magnet current of 1A, the diamond and BN cases display surprisingly different current-characteristics, in contrast to what we have seen previously, when we performed similar experiments in an oil-diffusion pumped vacuum chamber [8]. The surprisingly low discharge current seen for the diamond case is the result of a new mode of operation, which, to the author's knowledge has never before been seen in a Hall discharge. In this case, the thruster operated in a repetitively "pulsed" mode, with a frequency of ~ 3 kHz, and a duty cycle of about 1/100. This mode was very "stable" in that the discharge can survive indefinitely although it is not anticipated to be very efficient. That is because the discharge power is reduced by a factor of 10 in comparison to that of the BN case, resulting in a low propellant utilization, since the xenon mass flow rate is unchanged. The origin for this instability is not yet known, though we suspect that it may have some connection to the expected low secondary electron emission coefficient of diamond. In the case of the BN wall, the current characteristic is not unusual for this thruster. However, it could not be operated below about 200V because of a runaway instability, possibly due to an ionization spoke [11], which is very likely to be a precursor to the usual "breathing" mode (a behavior characteristic of co-axial Hall discharges [12]), characterized by strong amplitude oscillations most notably at higher voltages. The gradual rise in the current beyond 220V is unusual and not seen in co-axial discharges with BN walls, and is suggestive of an enhanced electron current, quite possibly due to the end wall effects, with a high flux of drifting electrons striking the end walls.

When the winding current is reduced to 0.5 A, the diamond-walled linear thruster was found to be between modes, with a transition occurring at a voltage centered about 200V. A slight hysteresis was found when returning to lower voltages after transitioning to the usual operation. As can be seen, this transition is rather abrupt, and it is apparent (and significant) that the diamond-walled discharge current, when operating at about ½ the peak magnetic field of that of the BN walled discharge, are comparable, suggesting that the near-wall conductivity is much lower in the case of the diamond channel. Oscillograms of the discharge current for the boron nitride wall case (1 A magnet current) and for the diamond wall case (at 0.5 A current) are compared in Fig. 4, whereas the oscillogram for the diamond wall case operating at 1A of magnet current is shown in Fig. 5. This lower average current "pulsed" regime is clearly apparent. The I-V characteristic for the 1 A winding current cases shown in Fig. 3, are reproduced in Fig. 6, together with the amplitude in the discharge oscillations. Again, it is seen that the relative strength of these oscillations is much higher for this low current pulsed mode, when diamond walls are used.

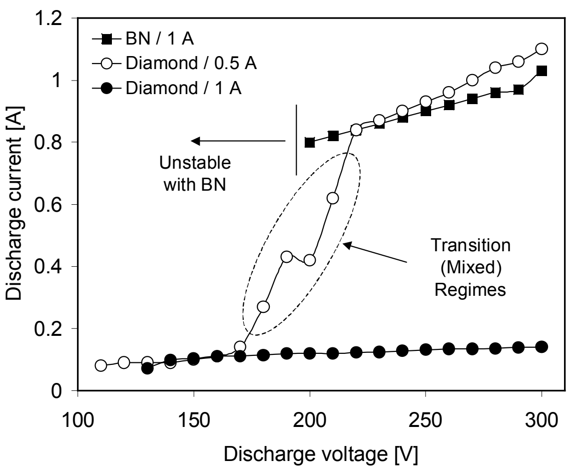


Fig.3. A comparison of the I-V discharge characteristics of the linear thruster with either boron nitride or diamond walls.

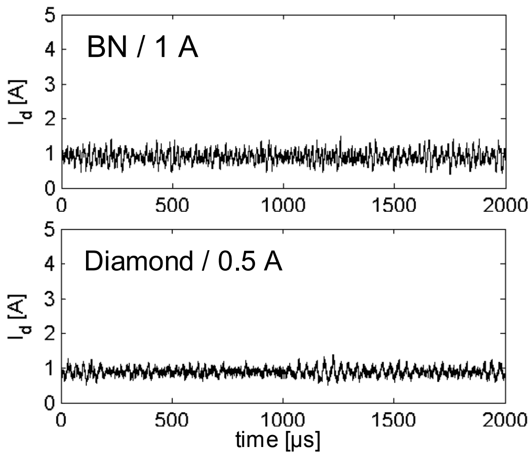


Fig. 4. Oscillogram of the discharge current for boron nitride walls (1 A magnet current) and diamond walls (0.5 A magnet current).

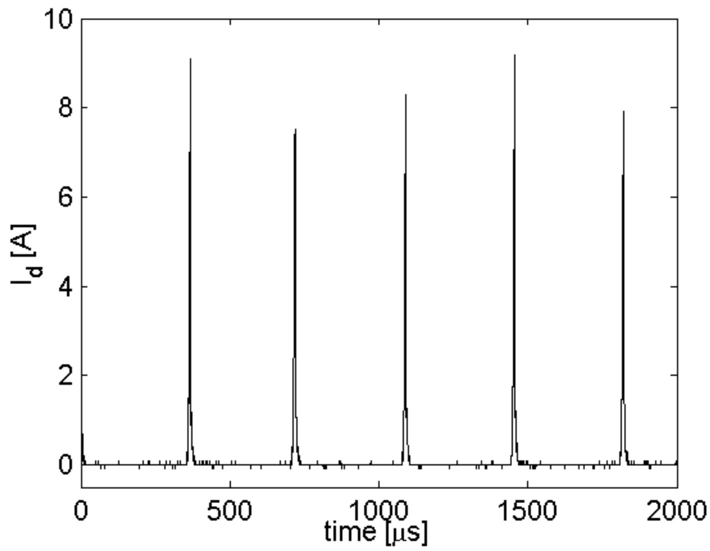


Fig. 5. Oscillogram for the case of diamond walls, with the discharge in the "pulsed" mode (1A magnet current).

Spectral maps of the discharge oscillations for the two cases of Fig. 6, are shown in Fig. 7. The voltage-dependence of the strongest oscillations seen in the case of the BN channel is characteristic of the breathing mode, which we have extensively studied previously, for the BN walled linear thruster [13]. The spectrum for the diamond-wall thruster broadens with increasing voltage and shows strong narrow-band harmonics whose frequencies do not seem to be influenced by the discharge voltage. It still remains unclear what role, if any, the power supply circuit may have on this pulsed mode. The typical response time of the power supply is ~50 ms, well above the time between each pulse (~0.4 ms), which excludes a simple resonance between the discharge and power supply.

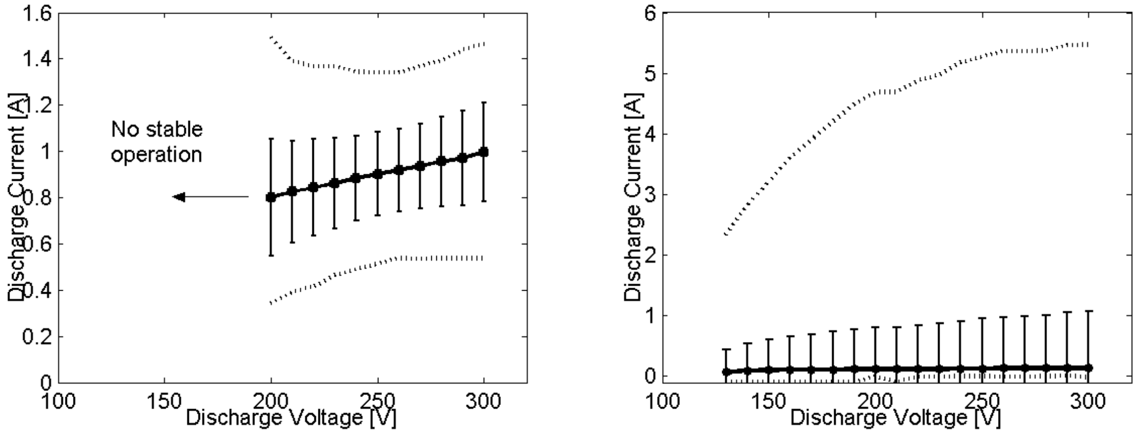


Fig. 6. Oscillation amplitudes of linear Hall thruster. Left: With boron nitride walls. Right: Diamond walls. Error bars indicate the standard deviation of the oscillating current.

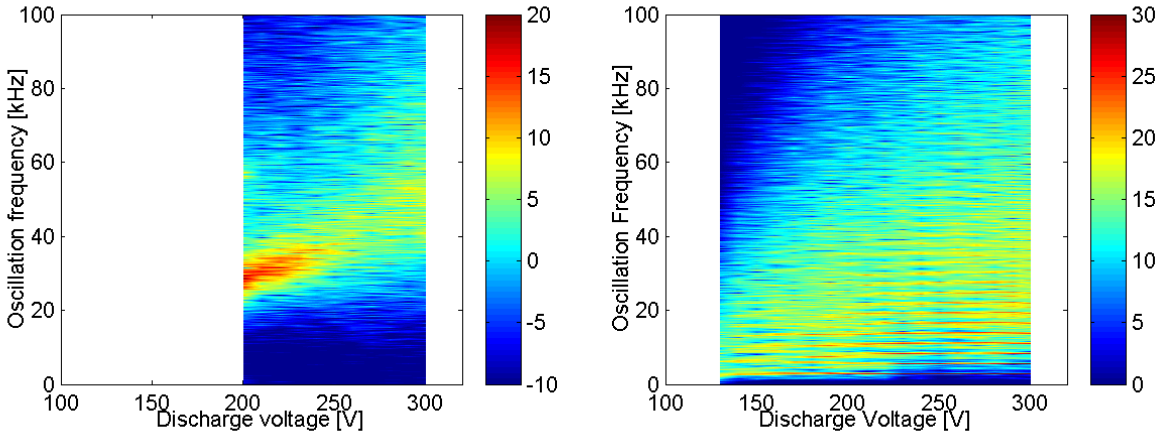


Fig. 7. Spectral maps for the discharge conditions as those cases shown in Fig. 6. Left: Operation with boron nitride walls. Right: Operation with diamond walls.

**III.2 Streak Camera Imaging of Transient Phenomenon**

Preliminary results are shown in the left panel of Fig. 8, for the high-speed imaging of a narrow region of plasma along the width of the discharge (boron nitride wall, 1 A magnet current, 200 V), when viewed end-on, as illustrated by the red marker in Fig. 3 (slit aligned with the magnetic field direction). The time domain given by the maximum in the vertical scale is 330 μs. The horizontal scale is approximately 2 cm. The structures in this image represent the successive cycles corresponding to the breathing mode instability at about 25 kHz. It is noteworthy that within these larger coherent structures is a seemingly random distribution of smaller structures, that have spatial scales that are sub-millimeter, and frequencies that are some 5 – 10 times greater than those of the breathing mode. These higher frequency disturbances are also apparent in the temporal variation at any one location, as illustrated by a “cut” through the data near the center of the discharge channel (see the right panel of Fig. 8). We speculate that these higher frequency components are transit time instabilities, although a definitive assignment requires further experiments.

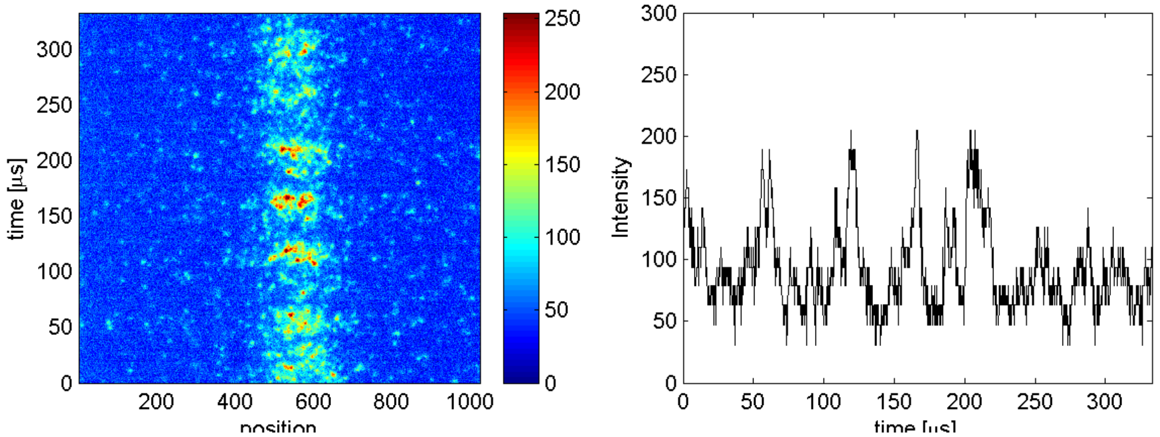


Fig. 8. Streak images of plasma emission with image of streak camera slit aligned perpendicular to the drift direction as seen in Fig. 3. Left: full image (330 µs × 2 cm). Right: Single-pixel stripe through the position corresponding to about the channel centerline.

In the left panel of Fig. 9, we show a similar streak, this time with the image of the slit oriented along the drift direction (see Fig. 3 for reference), and for the case of a diamond-walled channel (operating at 0.5 A magnet current, and 210 V). Here, the temporal scale is 500 µs, and the spatial dimension is also about 2 cm. In the image shown, the left direction is the direction of the Hall current, while time is from the bottom upwards. The appearance of horizontal bands is direct evidence of a somewhat spatially-inhomogeneous breathing mode, seen here to be about 18 kHz. It seems that the strength of the emission is greater on the side favored by the Hall drift. The finer features at temporal and spatial scales smaller than the features of the breathing mode, once again, are speculated to be due to transit-time instabilities. The right panel of Fig. 9 is a corresponding stripe through the image at a pixel column of 200. It is very apparent from this temporal trace that there are finer frequencies riding on top of the breathing mode. The small structures are about a few hundred microns in size along the **E**×**B** direction – apparently smaller than the spatial scales of these structures in the direction of the magnetic field, though more research has to be carried out to identify spatial anisotropies in the turbulent, higher frequency features.

These first images, although preliminary, illustrate the powerful insight that can be gained from this diagnostic (data on short-wavelength instabilities) – which must otherwise be obtained from a rake of very small (and invasive) Langmuir probes, or possibly an array of optical fibers. To our knowledge, these streak images represent the first, true, spatial-temporal analysis of a Hall discharge plume, albeit with spatial resolution only along the direction parallel to, or perpendicular to the direction of the electron drift.

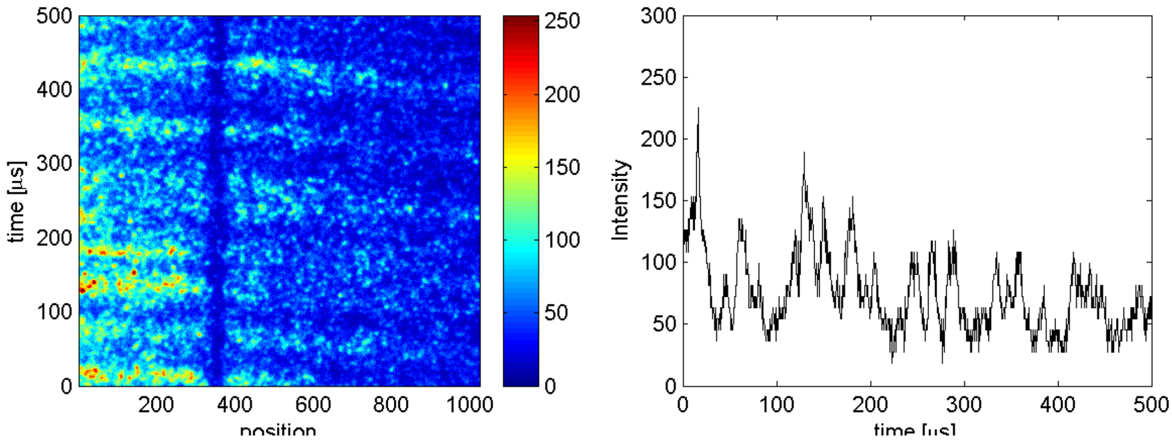


Fig. 9. Streak images of plasma emission with image of the streak camera slit aligned along the drift direction as seen in Fig. 3. Left: full image (500 µs × 2 cm). Right: Single-pixel stripe through the position corresponding to the 200$^{th}$ pixel column (favoring the side of the thruster towards **E**×**B** direction).

## IV. SUMMARY

In this paper, we have presented the results of ongoing studies aimed at understanding wall effects in Hall thrusters, and, in particular, in a linear-geometry Hall thruster with an open electron drift current. Experiments were conducted with two channel wall materials – boron nitride, and polycrystalline diamond plate. These experiments were repeat experiments carried out in a cryogenically-pumped vacuum facility, in an attempt to reconcile the results of prior similar studies [8] carried out in a chamber that was pumped by un-baffled silicone oil-based diffusion pumps. The results obtained here were notably different, in that for the boron nitride case, operation at low voltage and at high magnetic fields (800 Gauss) was not possible due to the onset of a strong ionization instability, whereas for the diamond channel case, only an unusual low average current, pulsed mode was "stable". This pulsed mode transitioned to the usual mode of Hall thruster operation at lower magnetic field strengths, though the transition was abrupt, and centered at a discharge voltage of about 200V. To our knowledge, this pulsed operation has never before been seen in a Hall discharge of any sort. The reason for this behavior is not entirely certain, although we suspect that it must have some connection to the secondary electron emission properties of polycrystalline diamond. Perhaps more important is the finding that the discharge behavior with either diamond or BN as the wall material was notably different in the cryogenically-pumped chamber, in comparison to similar operating conditions in the un-baffled diffusion pumped facility. These differences are attributed to the contamination of the walls with the residue of either silicone-based pump oil, or sputtering from the chamber walls (the later would still be a factor in the present studies).

Our paper also described the first true temporally and spatially resolved characterization of the discharge by use of a high-speed streak camera. The preliminary streak images of spatial structure aligned to the hall drift direction and also orthogonal to the Hall drift (along the direction of the magnetic field) confirm the existence of a strong breathing mode under usual Hall thruster operating regimes. It also reveals the presence of sub-millimeter scale spatial disturbances that are very turbulent, and at frequencies that are consistent with the so-called transit time instabilities. Future experiments will focus on the further study of both this unusual pulsed mode of operation, and the use of the streak camera to obtain some understanding of the interesting, turbulent nature of these unique plasma devices.

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