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Brian E. Beal & Alec D. Gallimore (Univ. of Michigan);
William A. Hargus, Jr. (AFRL/PRSS)

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The Effects of Cathode Configuration on Hall Thruster Cluster Plume Properties (PREPRINT)

Brian E. Beal and Alec D. Gallimore

Plasmadynamics and Electric Propulsion Laboratory

University of Michigan, Ann Arbor, MI 48109

William A. Hargus, Jr.

Spacecraft Propulsion Branch

Air Force Research Laboratory, Edwards AFB, CA 93524

ABSTRACT

Clusters of Hall thrusters may be used to produce electric propulsion systems capable of operating at power levels in excess of the current state of the art. One of the key factors to be considered in determining the optimum cluster architecture is the configuration of the electron-emitting cathode(s). This work presents experimentally determined plume properties and discharge current characteristics obtained with multiple thrusters coupled to a single cathode. Spatially resolved plasma density, electron temperature, and plasma potential data are presented during both single thruster and cluster operation. Measurements taken in this configuration are compared to previously published data obtained with each thruster coupled to its own independent cathode. Critical plasma parameters in the cluster plume are shown to be strongly influenced by the location of the hollow cathode.

Introduction

Many future spacecraft will use electric propulsion systems for station keeping, rephasing, and orbit topping applications, as well as deep-space missions. Due to its combination of high reliability and high thrust density at moderately high specific impulses, the Hall thruster is particularly well suited to many of these missions. The Hall thruster is an annular device in which a propellant, usually xenon, is ionized and then accelerated by electrostatic forces to create propulsive thrust. In this type of device, electrons from a thermionically emitting hollow cathode proceed upstream toward a positively biased anode where they ionize the injected propellant. A radial magnetic field imposed by an electromagnetic circuit impedes the motion of electrons toward the anode. The magnetic field strength is such that the electron gyroradius is much smaller than the characteristic dimensions of the device, while the ion gyroradius is much larger. This arrangement facilitates a strong axial electric field within the plasma and provides for acceleration of the positively-charged xenon ions. Upon exiting the device, the ion beam is neutralized by electrons from the hollow cathode, thus maintaining quasi-neutrality within the plasma plume. The crossed electric and magnetic fields cause electrons in the discharge channel to drift azimuthally, thereby creating a closed-drift electron Hall current from which this type of thruster derives its name.

One method being considered for reaching the increasing power levels required for future applications involves clustering multiple devices of moderate power to reach the total throughput required.[1,2] The clustered approach offers several advantages compared to using a single monolithic thruster including improved system reliability, modularity, and the ability to throttle the system by simply turning on or off the appropriate number of thrusters. Throttling the system in this way allows the cluster to operate at various powers without running any individual thruster at off-design conditions and may prove beneficial for missions in which either the propulsive needs or the available power vary with time.

While using a cluster of high-power thrusters for primary propulsion appears to be advantageous for many missions, there are several systems integration issues that must be considered before clusters can be used in flight.[1,2] For example, it is imperative that the interaction of the plasma plumes both among the thrusters and with the spacecraft be understood. In an effort to address this issue, a cluster of four Busek BHT-200-X3 200-watt class devices has been studied in detail and reported on previously.[3-7] In these studies, plasma properties such as electron number density, electron temperature, and plasma potential were measured downstream of a cluster and compared to properties measured downstream of a single thruster. This work demonstrated the methods by which knowledge of plasma parameters downstream of a single thruster can be used to accurately predict critical plasma parameters downstream of a multi-thruster array when each thruster is operated independently; i.e., with its own dedicated hollow cathode and power circuit.[6,7] In this configuration, analytical methods were shown to be capable of predicting the electron number density, electron temperature, and plasma potential in a cluster plume to within the margin of error of typical plasma diagnostics.

Although the nominal (i.e., independent) cluster configuration considered previously may be preferred in many cases due to its favorable combination of modularity and scalability, there are some situations in which trade studies may show alternative cluster configurations to be advantageous. For example, it may be beneficial in some situations to operate a cluster of thrusters in parallel so that the entire assembly may be powered from a single, large power-processing unit (PPU) rather than several smaller ones. In other situations, performance benefits may be achieved by operating multiple thrusters from a single cathode. Since propellant injected through the hollow cathode is not accelerated through the engine, it provides no thrust and therefore reduces the overall specific impulse of the system. Clearly, operating multiple thrusters from a single cathode (without increasing the cathode mass flow rate or with an increase that is less than linear with emitted current) would mitigate the effects of this loss mechanism compared to operating each thruster with its own cathode. Although reliability considerations almost certainly eliminate the possibility of using only a single cathode with an entire multi-thruster array in an operational cluster design, one can envision the use of a single cathode with one or more back-up units for the entire cluster or, a reconfigurable system that could support shared cathode operation in the event of a single-unit failure. The two latter configurations would provide significant risk reduction for spacecraft designers. This article examines some of the technical issues and challenges related to each of these alternative configurations.

Experimental Apparatus

Cluster

The cluster used in this experiment was comprised of four Busek BHT-200-X3 200-watt class Hall thrusters. An earlier version of this thruster was reported to operate at an anode efficiency of 42% and specific impulse of 1300 seconds while providing 12.4 mN of thrust at the nominal operating conditions.[8] Each thruster had a mean discharge channel diameter of 21 mm and was operated on xenon propellant. The thrusters were arranged in a 2x2 grid with approximately 11.4 centimeters between the centerlines of nearest neighbors. Typical operating conditions for the BHT-200 are given in Table 1.

The naming convention and coordinate system used throughout this experiment are shown in Fig. 1. As shown, the thrusters were labeled as TH 1-4 beginning in the upper left-hand corner and proceeding counterclockwise when viewed from downstream. The origin of the coordinate system was defined as the midpoint of the cluster in the displayed X-Y plane. The Z coordinate measured the distance downstream of the thruster exit plane. A three-dimensional positioning system was used to sweep probes through the plasma plume.

Several different experimental configurations were tested to explore the various modes of cluster operation discussed in the previous section. In the first arrangement, both thrusters 2 and 3 were operated in parallel from a single discharge power supply. The main goal of operating the thrusters in parallel was to examine the possibility of cathode current sharing between the devices through the plasma plume. The electromagnet, keeper, and cathode heater circuits remained separate between the thrusters. The current emitted by each cathode was measured using powered Hall effect sensors.

In the second experimental configuration, two thrusters were operated from a single hollow cathode to examine the effects of cathode number and placement on plume properties. This was accomplished with two separate cathode arrangements. In one case, two thrusters were operated from cathode 3. Measurements were conducted at the Air Force Research Laboratory (AFRL) with thrusters 3 and 4 operating from cathode 3, while the shared cathode tests at the Plasmadynamics and Electric Propulsion Laboratory (PEPL) used thrusters 2 and 3 simply because of the different probe positioning systems used in these facilities. In both facilities, the xenon flow rate through the cathode remained constant at 1 sccm. The second neutralizer tested in this “shared cathode” configuration was a 6.35-mm-diameter Model HCN-252 hollow cathode available from Ion Tech, Inc. It was placed at the center of the cluster and operated with a constant 5 sccm xenon flow rate. Since there is no reason to suspect that the different cathode designs have any significant effect on the operation of the engines, comparing data obtained with the Ion Tech cathode to measurements made using the shared Busek cathode allows the effect of cathode location to be examined.

Vacuum Facilities

Two different vacuum facilities were used for various portions of the tests described here. The first was the Large Vacuum Test Facility (LVTF) at the University of Michigan. The LVTF is a stainless steel-clad, cryopumped chamber that is 6 meters in diameter, 9 meters long, and is described in detail elsewhere.[6] The LVTF features a maximum pumping speed of 240,000 liters per second on xenon and achieves a typical base pressure of approximately 1.5x10^{-7} Torr. For the tests reported here, only four of the seven available cryopumps were used resulting in chamber background pressures ranging from 1.1x10^{-6} Torr for single-thruster operation to 3.6x10^{-6} Torr (corrected for xenon) during operation of all four thrusters.

The second vacuum facility used in these experiments was Chamber 6 at AFRL. Chamber 6 is a 1.8 x 3.0 meter cylindrical, stainless steel vacuum chamber that is evacuated by one dual-stage cryopump and four single-stage cryopanels. During thruster operation, the chamber pressure stabilized at approximately 6.1x10^{-6} Torr for single thruster operation and 2.3x10^{-5} Torr for four-thruster operation. Both reported pressures are corrected for xenon.

Triple Probe

A symmetric triple Langmuir probe was used to acquire spatially-resolved measurements of plasma density and electron temperature throughout the cluster plume. This probe consisted of three tungsten electrodes insulated from each other by an alumina rod. The exposed section of each electrode was 5.0 mm long and 0.5 mm in diameter. The electrodes were spaced approximately two electrode diameters apart and the probe was sized to criteria that allowed the standard thin-sheath assumptions of probe theory to be applied.[9]

The methods used to determine electron temperature and plasma density from raw triple probe data have been presented in detail elsewhere.[6,7,10] Various previously published error analyses indicate that the absolute uncertainties in the calculated electron temperature and plasma density for typical triple probes are less than 30% and 60%, respectively.[11,12] The relative uncertainty between multiple data points measured using the same probe is believed to be considerably less than the absolute uncertainty due to the fact that many sources of error (e.g., uncertainty in probe dimensions, slight asymmetry of the electrodes, etc.) remain constant over the entire spatial region.

Emissive Probe

Plasma potential measurements were conducted using a floating emissive probe similar to the one described by Haas and Gallimore.[13] The emitting portion of the probe consisted of a loop of 0.13-mm-diameter tungsten filament, the ends of which were inserted into double bore alumina tubing along with 0.51-mm-diameter molybdenum wire leads. Short lengths of tungsten wire were inserted into the alumina tube to insure contact between the emitting filament and molybdenum leads. The diameter of the emitting filament loop was approximately 3 mm. The normal to the plane of the loop formed by the emitting filament was oriented in the X direction shown in Fig. 1.

The emissive probe is a widely used plasma diagnostic whose operation is based on the premise that a thermionically emitting filament in a low-temperature plasma will approach the local plasma potential when its emitted electron current is sufficient to neutralize the plasma sheath.[14] In actuality, the floating potential of the emissive probe remains slightly below the true plasma potential due to space-charge saturation of the sheath. For heavy ions, such as xenon, Ye and Takamura have shown that the difference between the probe potential and the true plasma potential can be as much as 1.03 times the local electron temperature (in eV).[12] In the far field of the Hall thruster ($Z \geq 50$ mm), the error induced by this mechanism is less than 3 V. For this experiment, the current necessary to heat the probe was provided by a programmable power supply with floating outputs. At each location in the plume, the current was steadily increased and the potential with respect to ground at the negative terminal of the power supply was recorded. This method allowed for verification of a well-defined plateau in the voltage-current trace indicating saturation of the plasma sheath. Considering that the voltage drop across the emitting filament never exceeded 6 V, the potential was measured at the negative terminal of the probe, and the electron temperature over the majority of the plume was less than 3 eV, the absolute uncertainty in the plasma potential measurements is estimated to be -3 and +8 V. The relative uncertainty between data points obtained using the same probe is believed to be significantly smaller than these values because the main source of uncertainty, the ~5 V potential difference across the emitting filament, remained essentially constant over the entire sampled range. The relative uncertainty between data points is therefore conservatively estimated to be ±2.0 V and is dominated by variations in electron temperature that can influence the small potential drop across the sheath surrounding the emitting filament.

Results

Discharge Current Characteristics

Discharge current characteristics recorded with two thrusters (TH2 and TH3) operating in parallel are shown as a function of time in Fig. 2. As shown, the current flowing through each anode is approximately 0.80 A and is nearly constant between the thrusters. This result is to be expected since the anode current is controlled primarily by the propellant mass flow rate through each engine. The cathode current traces, on the other hand, show distinct differences between the two units. Figure 2 clearly shows that cathode 3 supplied nearly all of the current necessary to operate both engines despite the fact that both cathodes were operated at identical mass flow rates and keeper currents. In this plot, the constant 0.50 A keeper current flowing through each cathode has been subtracted from the displayed traces to indicate the electron current flowing from the cathode to the anode.

The dominance of one cathode shown in Fig. 2 has potentially important implications for Hall thruster cluster design. In particular, it implies that thruster-cathode pairs intended for parallel operation will likely require active current balancing circuitry in the PPU to prevent one cathode from emitting more than the intended fraction of electron current. Similarly, any attempts to operate a single high-current thruster by supplying electron current from multiple low-current cathodes are likely to be unsuccessful unless precautions are taken to ensure equal loading between the emitters.

In the second cluster configuration studied, two Hall thrusters were coupled to a single, shared cathode. While no qualitative changes in discharge current characteristics were noted when two thrusters were coupled to a single cathode, distinct differences in operating characteristics were observed when a single thruster was operated from a distant cathode. The discharge current and cathode potential data displayed in Fig. 3 were obtained with both TH2 and TH3 coupled to cathode 3 in the LVTF. As shown, when TH2 was operated alone with cathode 3 (i.e., from Time=0 to approximately Time=2300 seconds), the discharge current was slightly higher than the nominal value of 0.80 A and the magnitude of current oscillations was also higher than observed in the nominal configuration.[6] When TH3 was ignited (at approximately Time=2300 seconds), the discharge current and magnitude of oscillations in TH2 decreased to near nominal levels. At the same time, the cathode potential increased (moved closer to ground) by about 2.5 volts, thus bringing it to near the nominal level.[6] When TH3 was then shut off (at approximately Time=3200 seconds) without changing any settings to TH2, the discharge current and cathode potential returned to their original, anomalous values.

Plasma Density

The triple probe was used to measure the plasma density in the plume for both shared cathode configurations: with the Ion Tech cathode shared and with cathode 3 shared. Measurements were obtained in Chamber 6 with TH3 and TH4 operating individually and simultaneously. Figures 4 and 5 show the profiles recorded at two different axial locations in the plume. Figures 4a and 5a depict density profiles recorded with two thrusters coupled to the Ion Tech cathode in the center of the cluster while Figs. 4b and 5b reflect the results of coupling to cathode 3. The thick black line in each figure depicts the density profile measured with each thruster operating in conjunction with its own Busek cathode; i.e., in the nominal configuration that was reported on previously.[6,7]

The plasma density measurements shown below reveal several interesting features related to shared cathode operation. First, the density downstream of a cluster operating with a single neutralizer cannot be predicted by simply summing the contributions from each individual thruster, as they can in the completely modular configuration.[6,7] This finding is particularly evident from examination of the data taken with cathode 3 shared. In this situation, TH3 shows no unusual plume characteristics when operating alone, which is to be expected since it is coupled to its own cathode. When TH4 is operated from this same cathode, however, the plume appears very diffuse and the peak density is more than a factor of 10 lower than the one measured with the engine coupled to its own cathode. Most surprising is that the density downstream of TH4 increases to near the nominal profile (within about 25%) when TH 3&4 are operated simultaneously. Clearly, operating both thrusters together changes the basic operation of TH4, thus eliminating the possibility of predicting the cluster plume via superposition. Incidentally, the data presented here confirm the previous statement that it is the location of the hollow cathode and not the specific design of the electron emitter that causes changes in the plume properties. This observation is obvious since the profile downstream of TH4 differs greatly from that of TH3 when each is operated individually with cathode 3. Increasing the distance between the thruster and the neutralizer seems to decrease the plasma density in the plume dramatically.

Examination of the data taken with the thrusters coupled to the central Ion Tech cathode reveals similar trends to those discussed above. Since this cathode is significantly farther away from the anode of each thruster than the cathodes of the nominal configuration, the lower density observed in the plume with each thruster running individually is consistent with the observations reported above. When both thrusters are operated together, the peak density downstream of each engine increases significantly compared to the level measured during individual operation. The plasma density with both thrusters operating from the central cathode, however, falls short of the ones measured with cathode 3 shared as well as those measured in the nominal configuration.

While Figs. 4 & 5 show clearly that the location of the cathode has a significant effect on the properties in the plasma plume, they do not explain why this is the case. To provide a more extensive database for studying possible causes, several additional sets of measurements were obtained at PEPL with TH2 and TH3 coupled to cathode 3. The configurations tested include:

(1) TH2 running alone.

(2) TH2 running and propellant flowing through TH3 (without a discharge). Testing with propellant flowing through TH3 allows the effect of collisions to be evaluated (qualitatively, at least) by increasing the local neutral density in the region between cathode 3 and TH 2.

(3) TH2 running with propellant flowing through TH3 and electromagnet 3 energized.

(4) TH 2 and TH3 operating simultaneously from cathode 3.

The plasma density profiles recorded at two different locations downstream of TH2 and TH3 at PEPL are displayed in Fig. 6. As shown in these plots, operating TH2 alone with cathode 3 resulted in a very diffuse plume with a low plasma density, which is in agreement with the behavior discussed above. The addition of flow through TH3, and the concomitant increase in local pressure, caused the density in the plume to increase by about a factor of two, although it remained far below the levels exhibited during normal operation. Energizing the electromagnet of TH3 had no discernible effect. Finally, igniting TH3 caused the plasma density downstream of both thrusters to increase dramatically to levels consistent with those reported previously for operation in the independent, modular configuration.[6,7]

Electron Temperature

The same triple probe used to obtain the density measurements presented in the previous section also gave the local electron temperature. Figures 7 and 8 show the electron temperatures measured in Chamber 6 at AFRL for the two different shared cathode experiments. As shown, the electron temperature downstream of a thruster tended to increase when it was operated with a distant cathode. For example, Fig. 7b shows that the temperature peaked at over 10 eV when TH4 was operated in conjunction with cathode 3 compared to approximately 3 eV during operation with a normally-positioned cathode.[6,7] Coupling to the Ion Tech cathode in the center of the cluster caused similar behavior and the peak electron temperature with one engine running rose to approximately 6 eV, as shown in Fig. 7a. As expected, the peak electron temperature decreased with increasing downstream distance. Even at an axial distance of 150 mm, or approximately 7 thruster diameters, the temperature downstream of TH4 remained approximately a factor of two higher when operated from a distant cathode compared to a local one. Regardless of which cathode was used, running multiple thrusters tended to reduce the electron temperature in the plume, bringing it closer to the normal level. Operating both thrusters in conjunction with cathode 3 caused the electron temperature to fall to almost exactly the nominal values, while it remained somewhat above normal during operation of the Ion Tech cathode.[6]

Electron temperatures measured at two axial locations in the LVTF with TH2 and TH3 sharing a single Busek cathode are shown in Fig. 9. As expected from the measurements obtained in Chamber 6, operating TH2 with the distant cathode 3 caused the electron temperature in the plume to rise well above the values measured in the nominal configuration.[6] In this mode, the temperature along the centerline of TH2 was approximately 6.5 eV at Z=70 mm and fell to less than 2.5 eV by 170 mm downstream of the exit plane. When an 8.5 sccm propellant flow was initiated through thruster 3 (without igniting a discharge), the electron temperature downstream of TH2 fell to about 3.5 eV at 70 mm and 1.5 eV by 170 mm downstream. This is similar to the behavior of the plasma density, which also showed significant changes when the average neutral density between the thruster and cathode was increased. Energizing the electromagnet of thruster 3 had very little effect on the temperature in the plume. When TH3 was operated in conjunction with TH2, the electron temperature fell to nominal levels and exhibited a high degree of symmetry between the plumes of the two engines, despite the fact that the hollow cathode was much closer to TH3 than it was to TH2. It can therefore be said that increasing the local pressure and running multiple thrusters both tended to decrease the electron temperature in the plume.

Plasma Potential

Like the plasma density and electron temperature, the plasma potential profiles in the plume also exhibited major changes from the nominal values (i.e., the values recorded when each thruster was operated with its own cathode) when the cluster was operated with a single, shared cathode. Figure 10 show potentials measured downstream of TH3 and TH4 for several different configurations at various axial positions. As shown, operating a single thruster from the 6.4-mm-diameter Ion Tech cathode located at the center of the cluster caused the peak potential at Z=50 mm to increase to more than 50 volts compared to a nominal value of just over 20 volts at this location. Operating both thrusters together with this cathode caused the peak plasma potential to fall to about 35 volts at this location. Similar to the behavior observed in the profiles of number density and electron temperature, coupling two thrusters to a single Busek cathode located in close proximity to one of the devices resulted in plasma potentials nearly identical to the ones recorded with each thruster operating independently. As expected, all of the potentials decreased with increasing axial distance. The relative positions of the curves, however, remained consistent, with the two-thruster, shared central cathode potentials falling between the nominal values and those measured with a single thruster operating from the central cathode.

Additional experiments were performed at PEPL to examine the effects of neutral density and magnetic fields on the plasma potential profiles. Like the triple probe measurements, these data were recorded downstream of TH2 and TH3 with both devices tied to cathode 3. The resulting data are presented in Fig. 11 below. The curves labeled "TH2 plus TH3 flow" represent data obtained with TH2 running and 8.5 sccm of xenon flowing through TH3, while the flow through TH3 was increased to 17 sccm for the curves labeled "TH2 plus TH3 double flow."

As shown in Fig. 11, the plasma potential downstream of TH2 was much higher at a given axial location when operated with cathode 3 than it was in the nominal configuration presented previously.[6,7] Since the boundary conditions of the potential field were set by the applied discharge voltage, these measurements depict a "pushing out" of the plasma potential such that a larger fraction of the potential drop occurrs outside of the discharge channel. The stronger electric fields outside of the engine may have a detrimental effect on thruster performance because they can be expected to lead to increased beam divergence. The plots below show that increasing the neutral density, and therefore the particle pressure, between the anode and the cathode reduced the potential in the plume somewhat. Finally, compared to the data measured with 8.5 sccm flowing through TH3, energizing electromagnet 3 appeared to cause slight decreases in the plasma potential directly downstream of TH2 and increases in the potential directly downstream of the cathode. The magnitude of the change caused by the magnetic field, however, was relatively small and no definitive trends can be determined from the available data. As expected, operating both thrusters together caused the potential in the plume to fall to almost exactly the values measured in the nominal configuration.

Analysis

The data presented in the previous sections indicate that the plasma plume properties and basic operating characteristics of a Hall thruster are both influenced by the coupling between the anode and cathode. The most important parameters controlling this process are likely to be the distance between the electrodes and the properties of the medium in the inter-electrode gap. While a rigorous analysis of the cathode coupling process is beyond the scope of the present work, the data presented here suggest that changes in electron mobility in the region between the anode and cathode may be the main mechanism driving large changes in plume properties as the cathode configuration is varied. This conclusion can be deduced by noting that increasing the neutral density in the plume, which would be expected to increase the electron collision rate and therefore the electron mobility, caused dramatic decreases in plasma potential and electron temperature compared to operating from a distant cathode at low neutral density. Similarly, activating an intermediate thruster between an original thruster and a distant cathode caused the plasma plume properties to return to near their nominal values. The last effect is most likely due to a significant increase in the effective electron mobility in the plume as a result of the increased plasma density. A more detailed explanation of the cathode coupling process and its effects on plasma plume properties has been presented elsewhere.[10]

One final observation of note is a possible discrepancy between the results presented here and other published measurements. While the data presented here show very pronounced changes in plasma plume properties when a thruster is operated with a distant cathode, both Walker[16] and Zakharenkov, *et al*,.[17] have found that Hall thrusters could be operated with cathodes placed several thruster diameters away with no apparent effect on performance. There are at least three possibilities that may be considered to explain this. First, since thrust was not measured as part of the present investigation, one could hypothesize that the definitive changes in plasma potential, electron temperature, and plasma density profiles discussed above occurred without being accompanied by a change in performance. We view this hypothesis as being very unlikely. Second, since both Walker[16] and Zakharenkov, *et al.*,[17] studied larger thrusters,[*] it might be reasonable to suppose that larger thrusters are in some way less sensitive to cathode location than the 200-watt engines studied here. Third, it is possible to hypothesize that there may be a certain design feature (not related to power level) that makes particular thrusters more or less sensitive to cathode position. The cause of the apparent discrepancy between the results presented here and those from studies of larger thrusters is not readily apparent from the available data. Again, we believe it is highly unlikely, however, that the rather dramatic changes in plume properties observed in this work could have occurred without a concurrent change in performance. A parametric study to ascertain why some thrusters are apparently more sensitive to cathode position than others is therefore suggested as a potentially fruitful avenue for further exploration of the characteristics of Hall thruster clusters operating in a shared-cathode configuration.

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[*] Walker used the 5-kW P5 thruster, Zakharenkov, et al. used a cluster of three 1.5-kW D-55 anode layer thrusters.

Conclusion

An extensive array of thruster operating parameters and plasma plume properties have been measured for clusters operating in both a parallel configuration and, in another case, with multiple thrusters coupled to a single cathode. The results show that parallel operation tends to allow one cathode to dominate the discharge by emitting the majority of the required electron current. When multiple thrusters are operated in conjunction with a single cathode, however, plume measurements show pronounced differences in plume properties depending on the number of thrusters in operation. In particular, operating a thruster from a distant cathode rather than a local one has been shown to cause increases in plasma potential and electron temperature, as well as a decrease in plasma density, in the near-field plume. When multiple thrusters were operated with a single cathode, the key plume parameters returned to near normal levels. The dependence of the basic operating properties of any given thruster on the characteristics of adjacent units makes the shared-cathode cluster configuration an unlikely choice for operational spacecraft. The nominal cluster configuration in which each thruster is operated with its own independent cathode is likely to be the most beneficial approach for development of high-power clusters.

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Table 1: Typical operating conditions for the BHT-200 Hall thruster.

Parameter	Value
Discharge Voltage (V)	250 ± 0.5
Discharge Current (A)	0.80 ± 0.03
Cathode Potential (V)	-8.5 ± 1.0
Electromagnet Current (A)	1.0 ± 0.03
Keeper Current (A)	0.5 ± 0.05
Keeper Voltage (V)	13 ± 1
Anode Mass Flow Rate (sccm)	8.5 ± 0.85
Cathode Mass Flow Rate (sccm)	1.0 ± 0.1

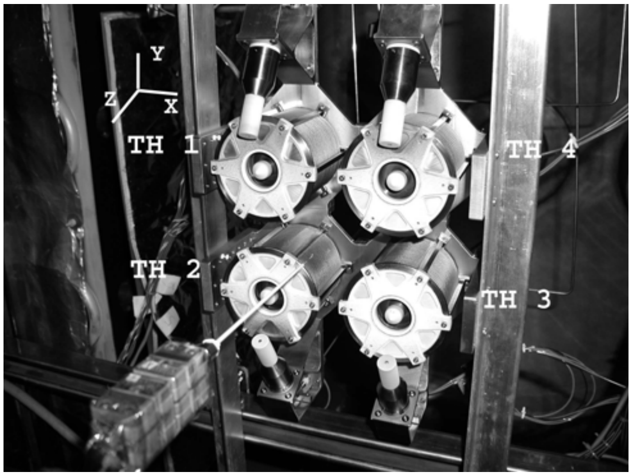


Figure 1

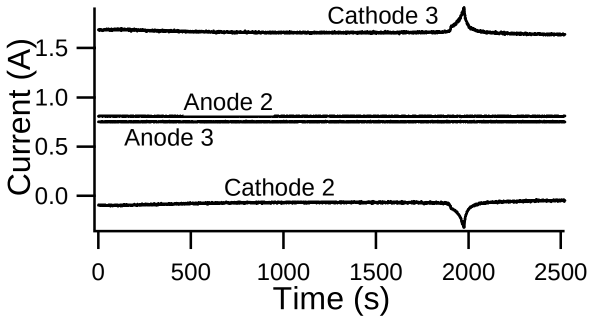

Cathode 3
Anode 2
Anode 3
Cathode 2
Current (A)
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
2500
Time (s)

Figure 2

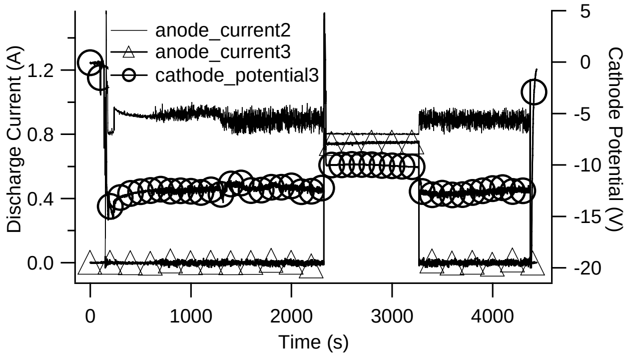
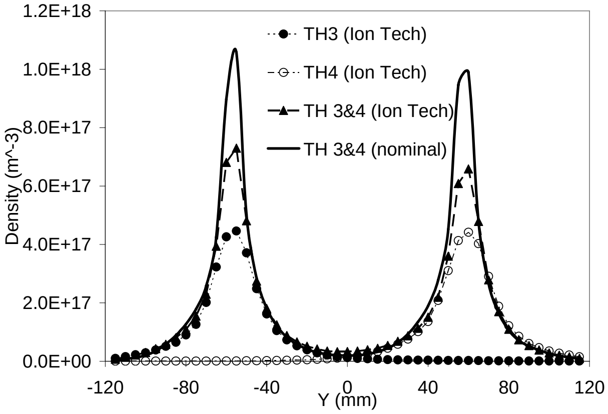
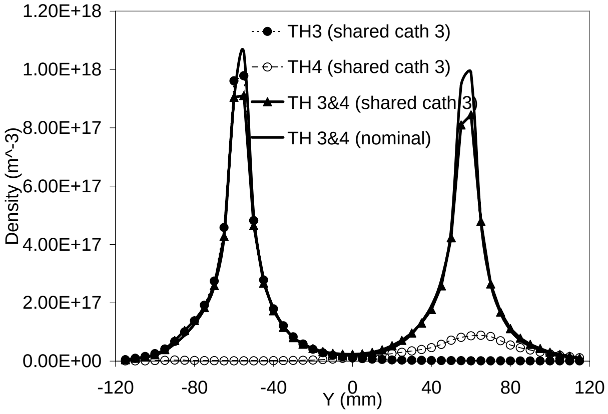

anode_current2
anode_current3
cathode_potential3
Discharge Current (A)
0.0
0.4
0.8
1.2
Cathode Potential (V)
5
0
-5
-10
-15
-20
0
1000
2000
3000
4000
Time (s)

Figure 3

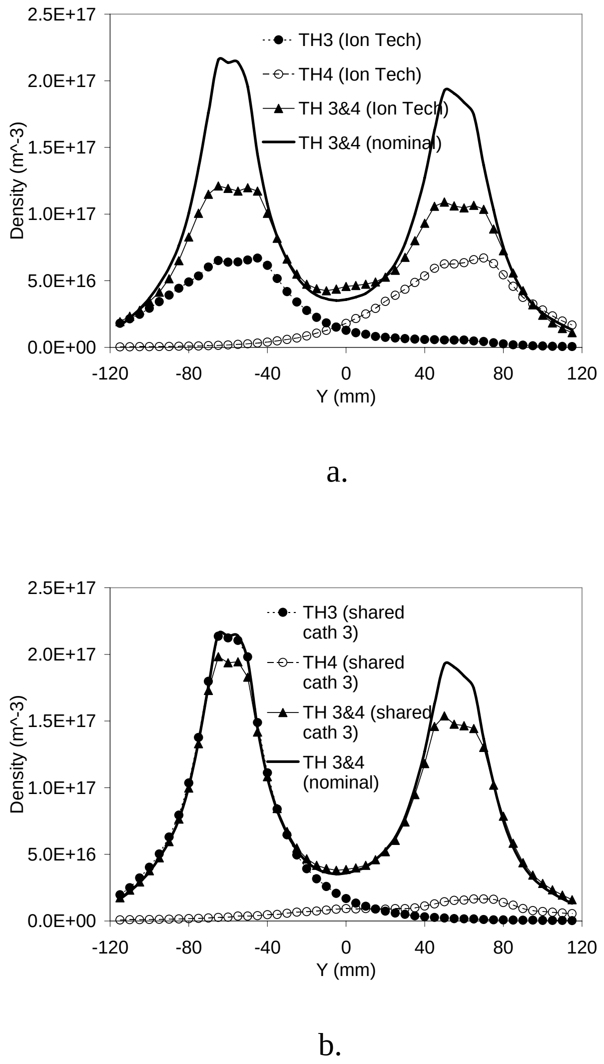

1.2E+18
1.0E+18
8.0E+17
6.0E+17
4.0E+17
2.0E+17
0.0E+00
Density (m^-3)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (Ion Tech)
TH4 (Ion Tech)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)

a.


1.20E+18
1.00E+18
8.00E+17
6.00E+17
4.00E+17
2.00E+17
0.00E+00
Density (m^-3)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (shared cath 3)
TH4 (shared cath 3)
TH 3&4 (shared cath 3)
TH 3&4 (nominal)

b.

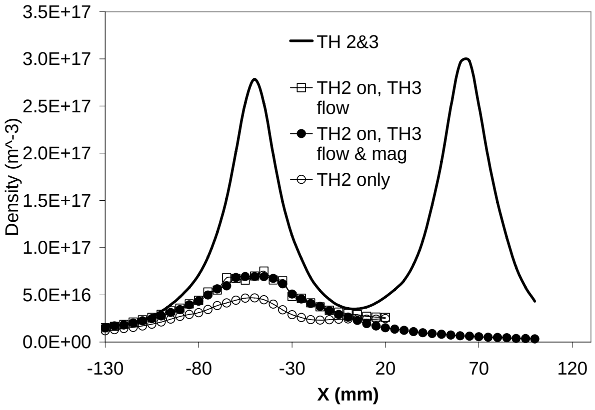
Figure 4


2.5E+17
2.0E+17
1.5E+17
1.0E+17
5.0E+16
0.0E+00
Density (m^-3)
TH3 (Ion Tech)
TH4 (Ion Tech)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (shared cath 3)
TH4 (shared cath 3)
TH 3&4 (shared cath 3)
TH 3&4 (nominal)

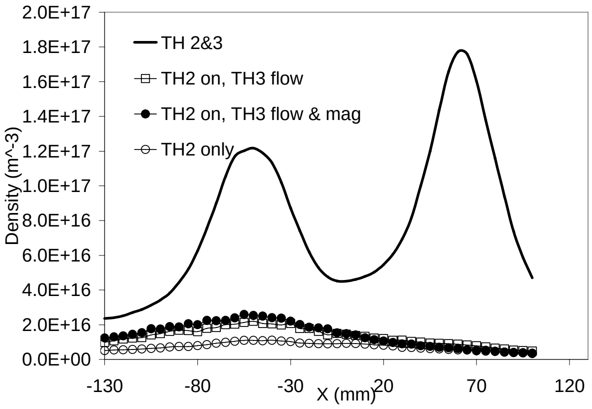
a.

b.

Figure 5

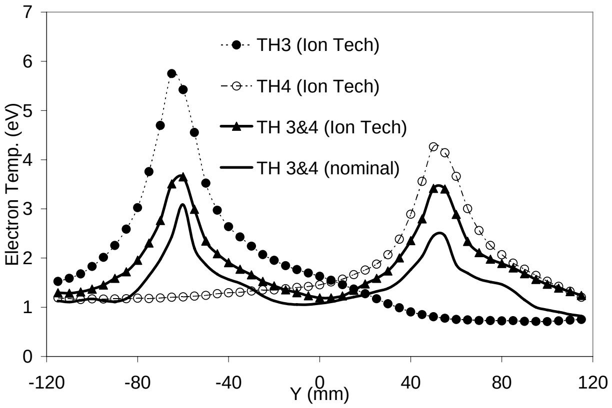

3.5E+17
3.0E+17
2.5E+17
2.0E+17
1.5E+17
1.0E+17
5.0E+16
0.0E+00
Density (m^-3)
TH 2&3
TH2 on, TH3 flow
TH2 on, TH3 flow & mag
TH2 only
-130
-80
-30
20
70
120
X (mm)

a.

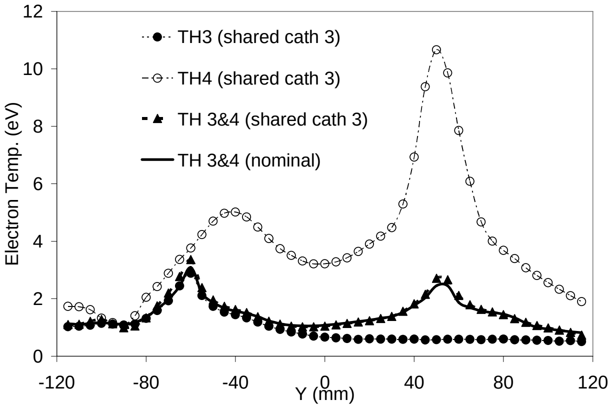

2.0E+17
1.8E+17
1.6E+17
1.4E+17
1.2E+17
1.0E+17
8.0E+16
6.0E+16
4.0E+16
2.0E+16
0.0E+00
Density (m^-3)
TH 2&3
TH2 on, TH3 flow
TH2 on, TH3 flow & mag
TH2 only
-130
-80
-30
20
70
120
X (mm)

b.

Figure 6

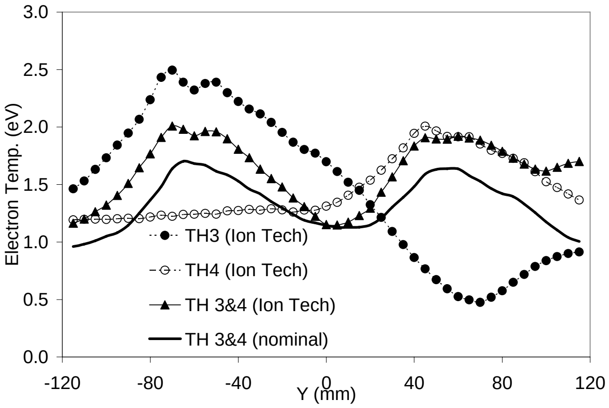

7
6
5
4
3
2
1
0
Electron Temp. (eV)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (Ion Tech)
TH4 (Ion Tech)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)

a.


12
10
8
6
4
2
0
Electron Temp. (eV)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (shared cath 3)
TH4 (shared cath 3)
TH 3&4 (shared cath 3)
TH 3&4 (nominal)

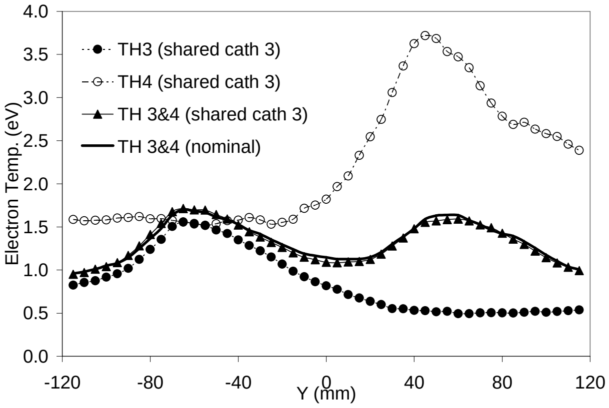
b.

Figure 7



3.0
2.5
2.0
1.5
1.0
0.5
0.0
Electron Temp. (eV)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (Ion Tech)
TH4 (Ion Tech)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)

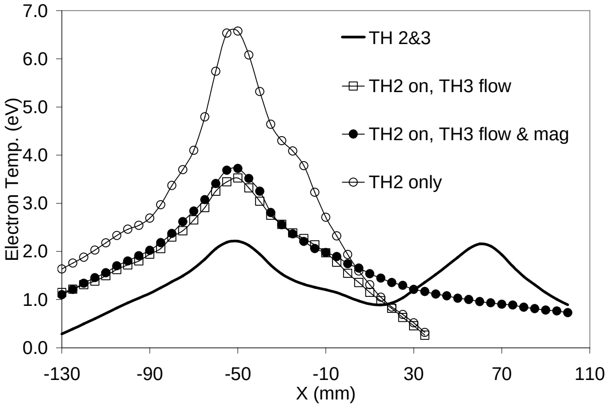
a.



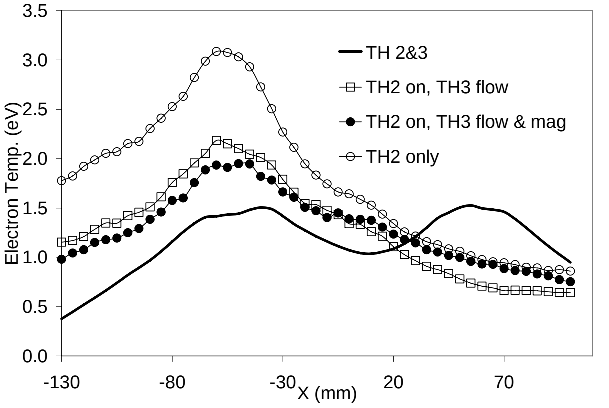
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Electron Temp. (eV)
-120
-80
-40
0
40
80
120
Y (mm)
TH3 (shared cath 3)
TH4 (shared cath 3)
TH 3&4 (shared cath 3)
TH 3&4 (nominal)

b.

Figure 8


7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Electron Temp. (eV)
-130
-90
-50
-10
30
70
110
X (mm)
TH 2&3
TH2 on, TH3 flow
TH2 on, TH3 flow & mag
TH2 only

a.


3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Electron Temp. (eV)
-130
-80
-30
20
70
X (mm)
TH 2&3
TH2 on, TH3 flow
TH2 on, TH3 flow & mag
TH2 only

b.

Figure 9

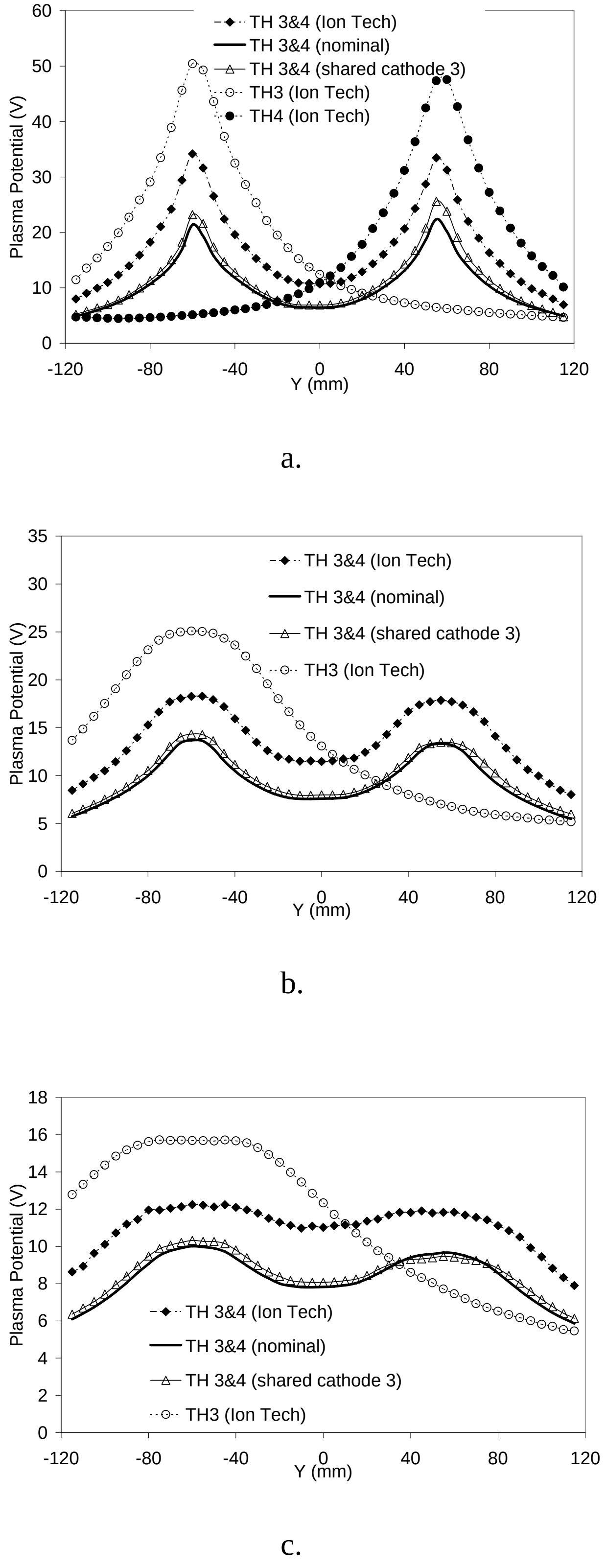
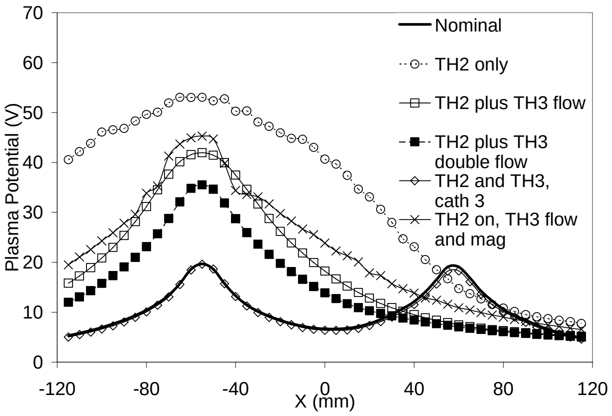
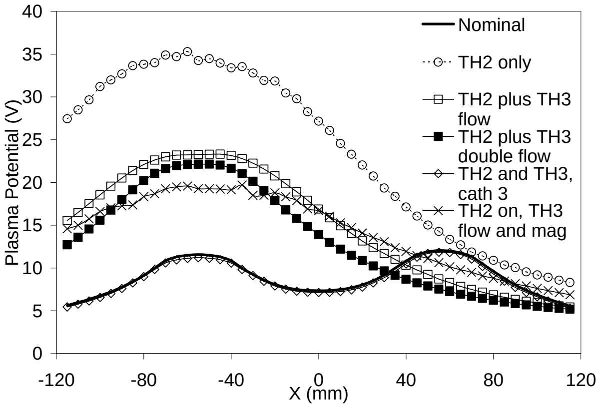

60
50
40
30
20
10
0
Plasma Potential (V)
-120
-80
-40
0
40
80
120
Y (mm)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)
TH 3&4 (shared cathode 3)
TH3 (Ion Tech)
TH4 (Ion Tech)
a.
35
30
25
20
15
10
5
0
Plasma Potential (V)
-120
-80
-40
0
40
80
120
Y (mm)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)
TH 3&4 (shared cathode 3)
TH3 (Ion Tech)
b.
18
16
14
12
10
8
6
4
2
0
Plasma Potential (V)
-120
-80
-40
0
40
80
120
Y (mm)
TH 3&4 (Ion Tech)
TH 3&4 (nominal)
TH 3&4 (shared cathode 3)
TH3 (Ion Tech)
c.

Figure 10


70
60
50
40
30
20
10
0
Plasma Potential (V)
-120
-80
-40
0
40
80
120
X (mm)
Nominal
TH2 only
TH2 plus TH3 flow
TH2 plus TH3 double flow
TH2 and TH3, cath 3
TH2 on, TH3 flow and mag

a.


40
35
30
25
20
15
10
5
0
Plasma Potential (V)
-120
-80
-40
0
40
80
120
X (mm)
Nominal
TH2 only
TH2 plus TH3 flow
TH2 plus TH3 double flow
TH2 and TH3, cath 3
TH2 on, TH3 flow and mag

b.

Figure 11

Captions:

Figure 1: The coordinate system and thruster naming convention used throughout this article. For some tests, an additional cathode (not shown) was placed at the geometric center of the cluster.

Figure 2: The anode and cathode currents recorded during parallel operation of two thrusters.

Figure 3: Operating characteristics of two Hall thrusters coupled to a single hollow cathode.

Figure 4: Density profiles recorded 50 mm downstream of TH 3&4 during operation with a.) a shared cathode in the center of the cluster and b.) cathode 3 shared.

Figure 5: Density profiles recorded 100 mm downstream of TH 3&4 during operation with a.) a shared cathode in the center of the cluster and b.) cathode 3 shared.

Figure 6: Density profiles recorded downstream of TH 2&3 during operation from cathode 3 at a.) Z=70 mm and b.) Z=120 mm.

Figure 7: Electron temperature profiles recorded 50 mm downstream of TH 3&4 during operation with a.) a shared cathode in the center of the cluster and b.) cathode 3 shared.

Figure 8: Electron temperature profiles recorded 100 mm downstream of TH 3&4 during operation with a.) a shared cathode in the center of the cluster and b.) cathode 3 shared.

Figure 9: Electron temperature profiles recorded downstream of TH 2&3 during operation from cathode 3 at a.) Z=70 mm and b.) Z=120 mm.

Figure 10: Plasma potential profiles measured downstream of TH 3&4 at a.) Z=50 mm, b.) Z=100 mm, and c.) Z=150 mm for various cathode configurations.

Figure 11: Plasma potential profiles recorded downstream of TH 2&3 during operation from cathode 3 at a.) Z=70 mm and b.) Z=120 mm.