

Ion velocity distributions in an SPT-100 Hall thruster

IEPC-2017-132

*Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology – Atlanta, Georgia – USA
October 8–12, 2017*

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Ion velocities in the discharge channel and near-field plume of an SPT-100 Hall thruster are mapped using Laser-Induced Fluorescence (LIF). The $5d[4]_{7/2} - 6p[3]_{5/2}$ excited state xenon transition is used to probe axial, radial and azimuthal ion velocities. Time-averaged measurements reveal the overall structure of the plume, while time-resolved measurements of ion velocity distributions synchronized to the thruster discharge current oscillations provide insight into the dynamic nature of thruster operation. Time-resolved measurements implemented using a sample-hold scheme with $1 \mu s$ resolution revealed fluctuations in LIF signal intensity and ion velocity are correlated with the dominant 19.8 kHz discharge current oscillation frequency. These measurements imply shifting in the position of the ionization and acceleration regions dependent on the phase of the thruster breathing mode cycle.

I. Introduction

ONE of the most prolifically used Hall thrusters on the market is the Stationary Plasma Thruster model SPT-100. Manufactured by the Russian company Fakel, the SPT-100 was made available to western satellite manufacturers beginning in the early 1990's for flight qualification. The SPT-100 has extensive flight heritage on Russian and United States satellites. It is currently the baseline thruster being used by the US satellite manufacturer Space Systems Loral (SS/L). In August 2016, Fakel celebrated the flight of its 100th SPT-100, which occurred aboard a SS/L satellite.¹

The SPT-100 has been studied extensively in the United States over the past 25 years by research groups at institutions such as Jet Propulsion Laboratory (JPL),² NASA-Lewis Research Center (LeRC),³ the Air Force Research Laboratory (AFRL),^{4,5} Space Systems Loral SS/L^{6,7} and several universities.^{8–11} Early tests focused on confirming thruster performance and lifetime,^{12,13} followed by a series of studies investigating plume interactions with spacecraft components.^{14–16}

Studies by Manzella using emission spectroscopy¹⁷ to estimate propellant ionization fraction and laser induced fluorescence (LIF)¹⁸ to measure ion velocity distributions were the first non-intrusive optical diagnostics applied to this thruster. This work seeks to expand on the LIF velocimetry measurements by

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presenting an extensive spatial and temporal mapping of time averaged and time resolved axial and radial ion velocities throughout the plume of an SPT-100.

Time averaged measurements are presented for the discharge channel and throughout the near-field plume of the thruster from centerline to 65 mm off-center and out to 80 mm from the thruster exit plane. Time resolved measurements, obtained with 1 μ s resolution, are accomplished using a sample-hold method to synchronize ion velocity distribution functions (IVDFs) to quasi-periodic fluctuations in the thruster discharge current. These measurements are presented with a similar spatial domain as the time averaged measurements, with particular focus on positions along the discharge channel and centerline of the thruster to better elucidate the dynamics of propellant ionization and acceleration, as well as the mixing of various ion velocity populations in the near field plume. Both the time averaged and time resolved measurements of IVDFs are critical for validation of numerical simulations that can be used to predict on-orbit operation of these thrusters including performance and spacecraft interactions.

II. Experiment

LIF measurements for this study are performed in Chamber 3 at the Air Force Research Laboratory (AFRL) at Edwards AFB, CA. Chamber 3 is a cylindrical, stainless steel vacuum chamber, 3.3-m in diameter and 8-m in length. The facility operates on eight helium-cooled cryopanel, providing a maximum xenon pumping speed of 140,000 l/s. This facility is capable of achieving a background pressure of approximately 1.7×10^{-5} torr (corrected for xenon) during nominal SPT-100 thruster operation. As described below, extensive measurements were taken of time averaged LIF velocimetry at this nominal operating condition. Additional, time resolved measurements were taken along the centerline of the thruster ($R = 0$) and along the discharge channel centerline ($R = 42.5$ mm).

A. SPT-100 Hall Thruster

Figure 1 provides an image of the SPT-100 Hall thruster operating, as well as a schematic of the thruster. The operating conditions used in this work are outlined in Table 1. The applied discharge voltage and anode mass flow rate were chosen to match previous testing at AFRL.⁴ The overall setpoint of the thruster operation is slightly different due to various factors including extensive operation of the available thruster prior to use in this study (>200 hours), use of laboratory power supplies and mass flow controllers rather than flight model equipment, and operation in a different vacuum chamber (Chamber 3 vs. Chamber 1 at AFRL). Comparison between these two studies is therefore meant to be qualitative in nature.

Typical discharge current characteristics during this study of the SPT-100 are shown in Fig. 2. An FFT of this trace shows that the thruster oscillates quasi-periodically at a frequency of 19.8 ± 4.09 kHz at the nominal operating pressure of 1.7×10^{-5} torr (corrected for xenon), resulting in a typical current cycle with a period of 50.3 ± 11.2 μ s.

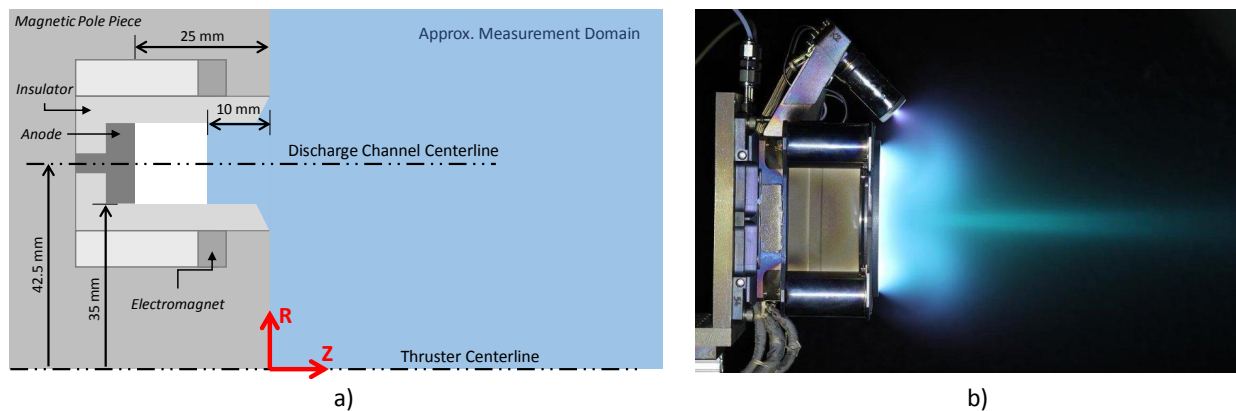


Figure 1. a) Schematic of SPT-100 Hall thruster including thruster dimensions and the Cartesian coordinate system used in this work. The origin is located at the tip of the nose cone. b) Image of SPT-100 Hall thruster operating on xenon.

Table 1. SPT-100 Hall thruster operating conditions.

Background Pressure	1.7×10^{-5} torr
Anode Flow	5.16 $\mu\text{g/s}$ Xe (52.46 sccm)
Cathode Flow	0.396 $\mu\text{g/s}$ Xe (4.03 sccm)
Anode Potential	300 V
Anode Current	4.24 A
Discharge Frequency	19.8 ± 4.09 kHz

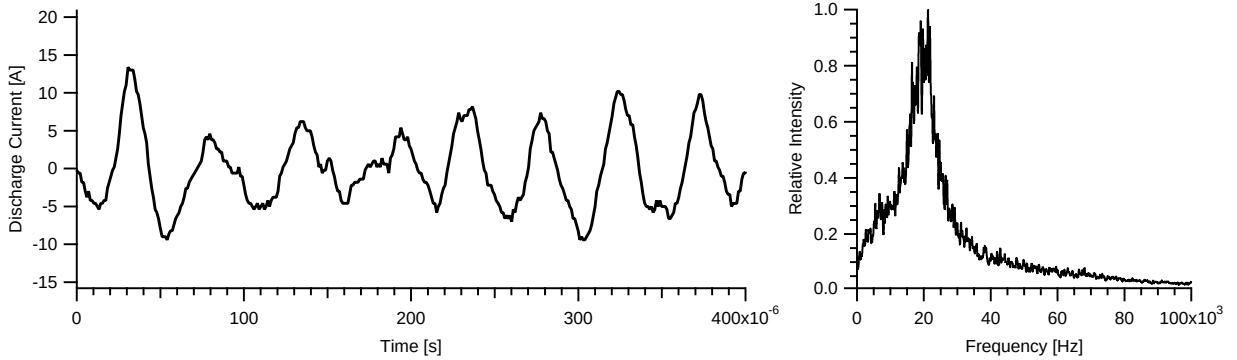


Figure 2. Thruster discharge current and associated FFTs for the SPT-100 nominal operating condition at 1.7×10^{-5} torr.

B. Laser Induced Fluorescence Velocimetry

Ion velocity measurements are accomplished by probing the $5d[4]_{7/2} - 6p[3]_{5/2}$ electronic transition of Xe II at 834.72 nm (air). The upper state of this transition is shared by the $6s[2]_{3/2} - 6p[3]_{5/2}$ transition at 541.92 nm,¹⁹ used for non-resonant fluorescence collection. This transition has been utilized extensively throughout the electric propulsion community for time-averaged and time-resolved LIF velocimetry.^{18, 20–22}

Figure 3 depicts the optical train and associated equipment used in this experiment.²³ A New Focus Vortex TLB-6917 tunable diode laser is used to seed a TA-7600 VAMP tapered amplifier to achieve a probe beam output power of 82 mW. A saturation study was done prior to measurements showing that this laser power was well within the linear regime.

Beam pick-offs send portions of the beam into a Fabry-Perot (F-P) etalon for frequency reference, and an optogalvanic xenon reference cell (OGC) for a zero velocity spectral line reference. Homodyne detection allows us to probe the 9.03 GHz distant $6p'[3/2]_1 - 8s'[3/2]_1$ Xe I transition in the OGC.^{24–26} A typical 30 GHz laser scan is accomplished in ~ 8 minutes with a lock-in time constant of 3 seconds.

The majority of the probe beam (~ 68 mW) is sent through a beam splitter (BS3) to divide it into axial and radial components going through separate choppers before entering the vacuum chamber. The fluorescence induced by both the axial and radial probe is collected at a 45° angle from the probe beam axis using a 200 mm focal length lens with 75 mm diameter. The collimated fluorescence signal is directed through a window in the chamber side wall to a similar lens that focuses the collected fluorescence onto the entrance slit of the 125 mm focal length monochromator attached to a photomultiplier tube (PMT). Due to the 1:1 magnification of the collection optics, the spatial resolution of the measurements is determined by the geometry of the monochromator entrance slit (set to 1 mm width by 1.7 mm height) along with the sub-millimeter diameter of the probe beam. Choppers (Ch1 = 1.9 kHz, Ch2 = 2.5 kHz and Ch3 = 3.2 kHz) are used for homodyne detection of the OGC, radial and axial fluorescence signals, respectively. For the axial and radial beams, the resulting signal is a time-averaged measurement of the fluorescence excitation lineshape if the PMT signal is sent directly into a lock-in amplifier. To synchronize the LIF signal in time to the discharge current, a sample-and-hold scheme is implemented between the PMT and the lock-in. The

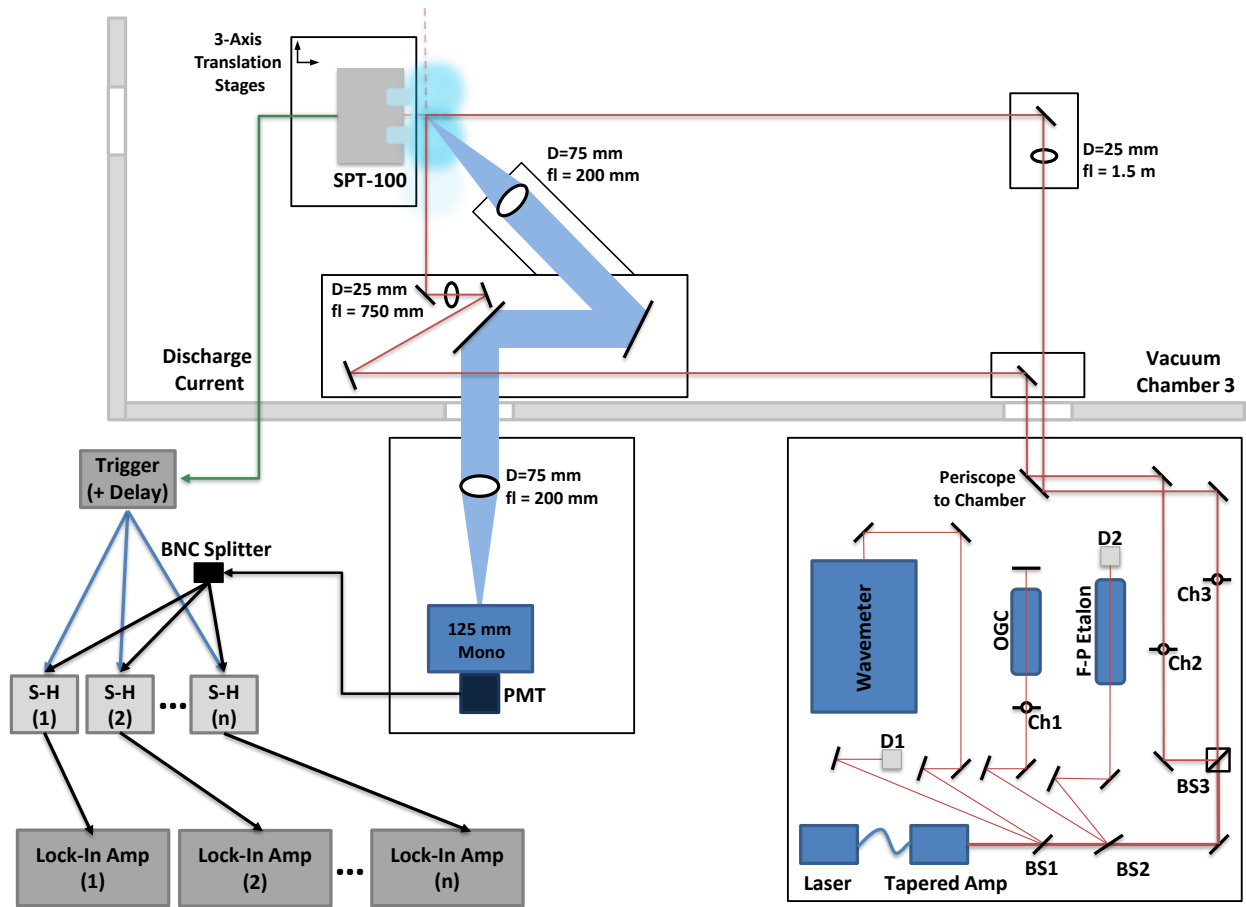


Figure 3. Laser optical train, including launch and collection optics, and parallelized sample-hold scheme.

development of this sample-hold scheme is described elsewhere.^{26–28}

The sample-hold method relies on synchronizing an acquisition gate to a given phase of the discharge current oscillation period of the thruster. The acquisition gate is generated by a pulse-delay generator triggered by a voltage comparator chip. During the acquisition gate, the PMT signal (emission plus fluorescence) is sampled, averaged and held until the next trigger, at which point the held signal is updated (once per period). The gate width chosen for this study was $1 \mu\text{s}$ to allow for multiple points of time resolution throughout the discharge current cycle. The sample-held signal is then sent through a lock-in amplifier for homodyne detection, resulting in a fluorescence excitation lineshape representing the IVDF at that particular phase of the discharge oscillation.

Translating the acquisition gate in time along the current cycle allows the full time evolution of the fluorescence excitation lineshape (and thereby IVDF) to be reconstructed. To reduce data acquisition time, the sample-hold circuitry in this work is parallelized by splitting the PMT signal into seven sample-hold branches, each triggered at different phases in the discharge current cycle with a $1 \mu\text{s}$ gate width, as shown in Fig. 3. In this work, seven lock-in amplifiers enabled measurements of IVDFs at seven temporal points during a single laser scan, for up to 21 points of time resolution in a typical set of three laser scans.

It is of note that due to the quasi-periodic, naturally drifting current oscillations in the SPT-100, the acquisition gate width is smaller than the $\pm 11.2 \mu\text{s}$ fluctuation in the discharge current period. This introduces some uncertainty in the time resolved measurements in terms of sampling at phases earlier or later in the discharge current cycle than desired. This results in a smoothing factor that makes our time resolved results more homogeneous than we have seen in thrusters with more periodic discharge current cycles.

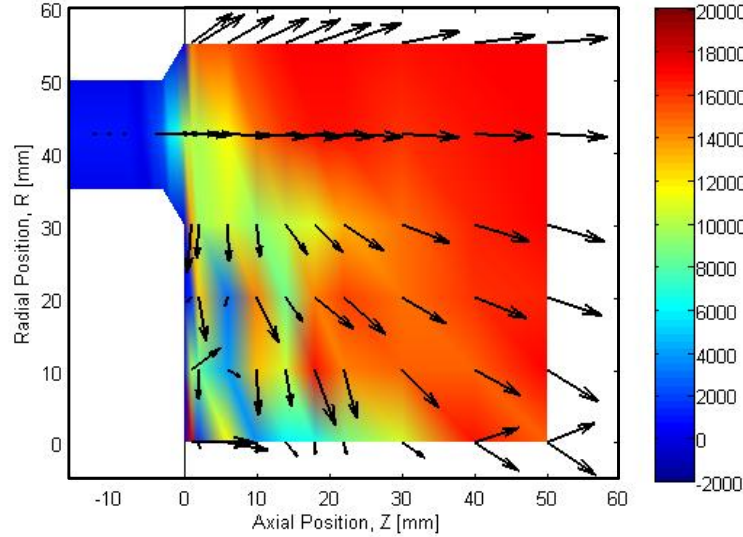


Figure 4. Most probable ion velocities in the discharge channel and near-field plume of the SPT-100 Hall thruster. Arrows indicate the direction of ion flow.

III. Results and Discussion

A. Time Averaged Velocities

Figure 4 provides the overall of time-averaged ion velocities throughout the channel and near-field plume of the SPT-100 Hall thruster. The color map in Fig. 4 represents the magnitude of the velocity. The direction of the ion flow is depicted using arrows with length and direction derived from the axial and radial velocity components of most probable, calculated using a Gaussian fit to the measured fluorescence excitation lineshapes at each spatial point.

On average, ions gain the majority of their velocity near the exit plane of the thruster discharge channel, accelerating radially outward in a cone from the channel walls. Ions accelerate to a maximum velocity of 18.1 km/s by 50 mm into the plume, after which they appear to continue at the same velocity on a ballistic trajectory. Geometric effects, or apparent evidence of collisionality from the crossing of the plume from one side of the channel to the opposite side creates a jet region along the centerline of the thruster, where there are multiple, distinct radial velocity populations seen at positions of $Z = +40$ mm and outwards. Closer to the thruster nose cone there is a region of turbulence where the overall magnitude of velocity is lower and varies in direction. Along the centerline, the radial velocity distributions are broad, square peaks that span ranges on the order of ± 15 km/s. While most probable fits to the IVDFs provide an indication of the bulk movement of the plasma in these cases, they do not do well to capture the multiple ion velocity populations.

IVDFs at each spatial point, particularly along the discharge channel centerline and thruster centerline, give a clearer picture of the ionization, acceleration and center jet mixing regions. Figure 5 provides the axial IVDFs inside the thruster discharge channel. The relative intensity of the fluorescence excitation lineshapes is representative of the population of ions in the probed metastable Xe II excited state ($5d[4]_{7/2}$) within the collection volume. This has previously been used as an indication of overall ion population.²⁶ The ion population steadily grows with a single peak approximately Gaussian in shape until -4 mm inside the exit plane (near the location of the max B-field). At this point, the fluorescence excitation lineshapes reach their peak intensity and the high velocity side of the distribution begins to dominate slightly. As ions accelerate out towards the exit plane, their population within the probed volume decreases and the shape of the distribution becomes more normal. The velocity continues to increase until it asymptotes at ~ 18.1 km/s, with population continuing to decrease at further distances into the plume, as shown in Fig. 6.

Figure 7 shows the corresponding radial IVDFs along the outside of the thruster channel. The velocities start at -130 m/s near the exit plane, reach -855 m/s at $Z = +18$ mm, then reduce to around zero velocity

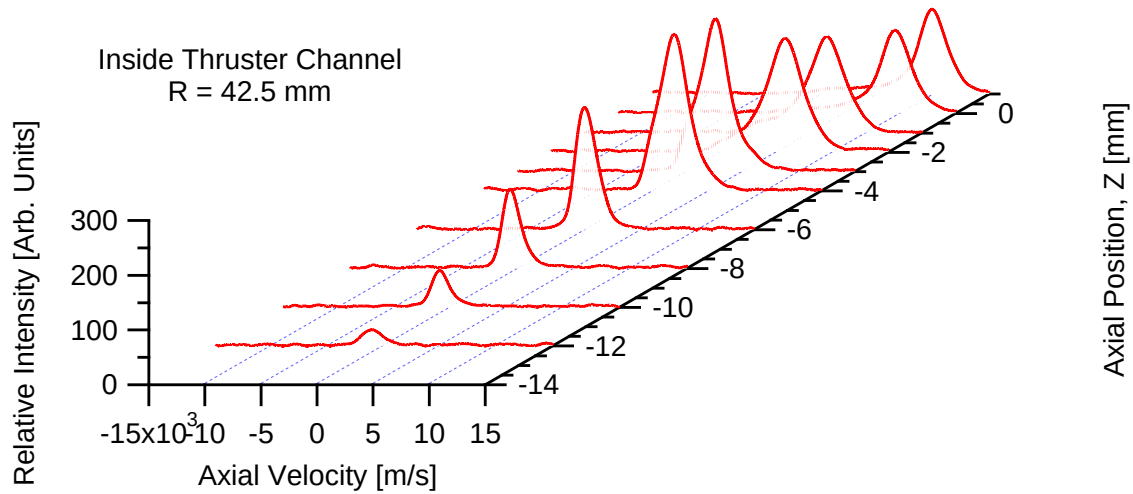


Figure 5. Time averaged axial ion velocity distributions at $R=42.5$ mm in the discharge channel of an SPT-100 Hall thruster.

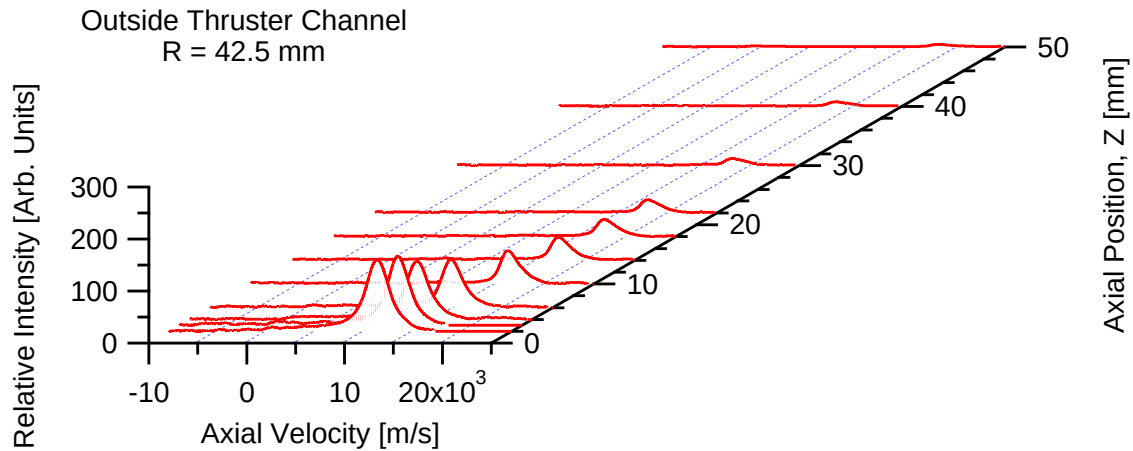


Figure 6. Time averaged axial ion velocity distributions at $R=42.5$ mm in the near-field plume of an SPT-100 Hall thruster. Note: the relative intensity is scaled to match that of Fig. 5.

with decreasing intensity further into the plume.

Figure 8 shows the axial ion velocities along the centerline of the thruster axis from the nose cone out to 80 mm into the near-field plume. Near the nose cone the IVDF has a broad single peak near zero velocity. Moving outwards into the plume, the distribution widens and develops a secondary higher velocity peak that starts to dominate around $Z = 16$ mm. The intensity of the higher velocity peak grows until a maximum at $Z = 60$ mm then remains relatively constant out to $Z = 80$ mm. These high intensities are indicative of the bright plasma jet seen in the middle of the thruster plume in Fig. 1b.

Figure 9 provides the corresponding radial IVDFs along the centerline of the thruster. The distributions are all centered near zero velocity with wide distributions near the nose cone, increasing in intensity outward into the plume. Starting at $Z = 40$ mm, two distinct peaks, one with positive radial velocity, the other with

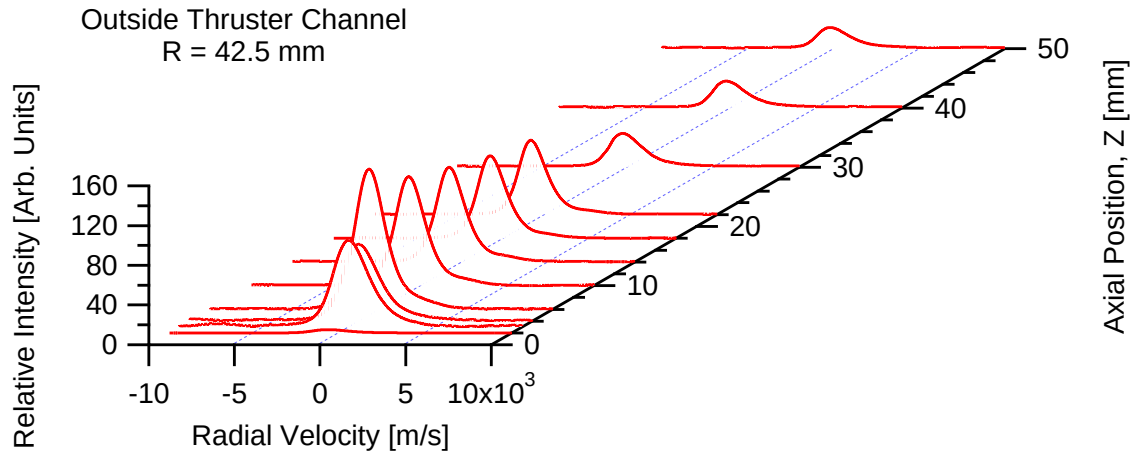


Figure 7. Time averaged radial ion velocity distributions at $R=42.5$ mm in the near-field plume of an SPT-100 Hall thruster.

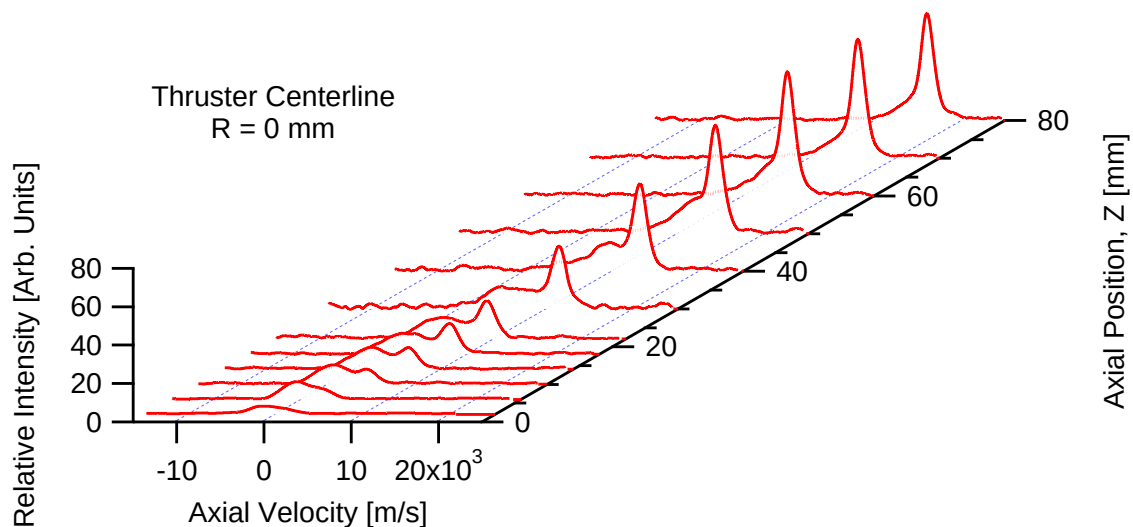


Figure 8. Time averaged axial ion velocity distributions at $R=0$ mm along the centerline of the SPT-100 Hall thruster.

negative velocity, begin to form and grow more prominent further into the plume. The two peaks are likely due to ion populations originating at opposite sides of the thruster discharge channel. The more diffuse and turbulent region near the nose cone has a very broad range of radial velocity in the ions (e.g. a FWHM of 18.2 km/s at $Z = 6$ mm), while the axial IVDF from Fig. 8 is more narrow (FWHM of 5.0 km/s at $Z = 6$ mm).

The time averaged IVDFs inside the thruster discharge channel and further into the plume along the centerline with multiple velocity populations are of particular interest due to their indication of the dynamics of thruster operation and the impact on spacecraft components due to plume interactions, respectively.

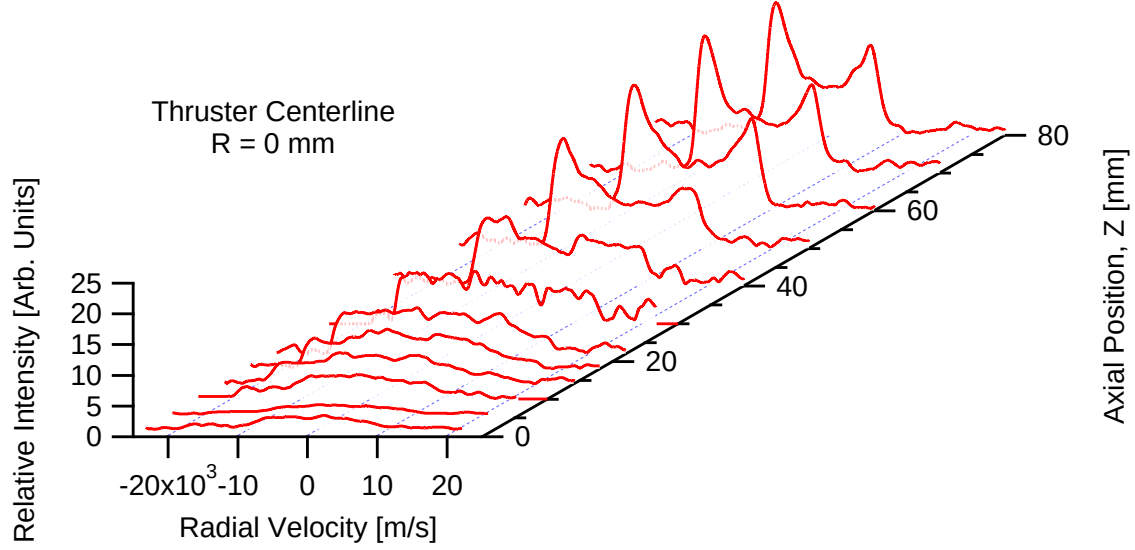


Figure 9. Time averaged radial ion velocity distributions at $R=0$ mm along the centerline of the SPT-100 Hall thruster.

B. Time Resolved Velocities

To further our analysis, we extend our measurements to be time resolved. Fig. 10 depicts the time resolved velocities throughout the channel and near-field plume of the SPT-100 at six different time points along a typical discharge current cycle. Comparing the magnitude and direction of the ion velocity at each time point to the time-averaged plot in Fig. 4, it is notable that the values are very similar for positions outside the discharge channel along $R = +42.5$ and $+55$ mm. The largest variations occur inside the thruster discharge channel, which is a region of ionization and peak acceleration, near the nosecone between $R = 0$ and $+30$ mm, and along the thruster centerline.

Near the nose cone, the magnitude of the velocities start on the order of 6 km/s when the discharge current is near zero. As the current drops, so does the velocity, as shown in Fig. 10b where velocities are between 2-4 km/s near the nose cone. As the discharge current ramps up, the velocities increase, with the maximums shown around 10 km/s in Fig. 10e, returning to lower velocity in Fig. 10f as the AC component of the discharge current starts to decrease back to zero.

For the majority of the near field thruster plume, time resolved IVDFs are composed of single velocity peaks in both the axial and radial directions, with the radial velocities at positions with $R < 42.5$ mm direction being composed of negative velocity peaks with tails extending out into positive velocity space. Weighted Gaussian fits of most probable velocity are good representations of the ion velocity populations in this region. However, the radial IVDFs along the centerline of the thruster in some cases have very distinct positive and negative radial velocity peaks. These are shown as two separate arrows along the centerline at positions of $Z = +40$ and $+50$ mm for some time points in the discharge current cycle. The strength of these double peaks ebb and flow, but remain relatively symmetric around zero radial velocity.

Looking more closely at the IVDFs for the regions of particular interest, Fig. 11 depicts the time resolved axial ion velocity from 10 mm inside the thruster discharge channel to $Z = 18$ mm into the near-field plume at $R = 42.5$ mm. In this figure, each vertical strip is an IVDF corresponding to a $1 \mu\text{s}$ chunk of time within the discharge current cycle. For each set of time resolved measurements presented in this section, averaging all of the IVDFs at a given position point results in an IVDF that matches the time averaged measurements seen in Figs. 5 through 9.

Looking at Fig. 11, the probed excited state ion population starts with a slightly negative, near zero velocity at $Z = -10$ mm inside the thruster discharge channel. Negative velocities have previously been attributed to gradient-driven field reversals at positions near the anode.^{26, 29, 30} Moving outwards towards the exit plane, the ion population increases with a maximum IVDF intensity seen at $Z = -4$ mm. This corresponds to a region of peak ionization. Within each spatial point there is little variation in the fluorescence

intensity with time, with the largest changes also occurring in the ionization region ($Z = -6$ to -2 mm) where the intensity is $\sim 75\%$ of its maximum as the discharge current decreases towards its trough, and reaches a maximum just before the maximum in discharge current.

During the initial acceleration, between $Z = -4$ mm and the exit plane, the FWHM of the velocity distributions are the widest, with spreads in velocity of around 6.6 km/s at $Z = -2$ mm. A slight temporal variation in most probable velocity also develops in this region. For example, at the exit plane, velocities start at their peak of 9.91 km/s at $t = 0$, dipping to 9.36 km/s at $t = 13.2 \mu\text{s}$. Similar ~ 500 m/s variations in most probable velocities are seen between $Z = -4$ and $+4$ mm. The velocities at each spatial point tend to increase, reaching their maxima about 1/4 oscillation period after the discharge current peak (90° out of phase), then fall to their minima as the discharge current begins its next ramp up. Further into the near-field plume, the IVDFs become progressively more narrow with less temporal variation as they reach the end of the potential drop. The majority of the acceleration occurs between $Z = -6$ mm and $+10$ mm, after which the axial ion velocity asymptotes to ~ 18.1 km/s.

Figure 12 provides the corresponding radial velocity measurements at $R = 42.5$ mm outside the thruster discharge channel. The velocities remain fairly constant in both time and spatial position. The IVDFs decrease in width and intensity outwards from the channel exit plane, much like the axial velocities.

Previous work on 600 W²⁶ and 400 W Hall thrusters,^{31,32} and a Diverging Cusped Field Thruster³³ have related the fluctuations in ion velocity and fluorescence excitation lineshape intensity to standard models of a Hall thruster breathing mode.^{34,35} The discharge current increases as an ionization front moves upstream, consuming neutral propellant and increasing the population of free electrons. The fluorescence intensity consequently reaches its maximum. The newly generated ions accelerate out of the channel according to the local potential field that is also changing with time. Ions obtain their maximum velocity soon after the point of peak ionization, and the ion density (and measured intensity) falls as the ions accelerate. The ionization front moves back downstream during the discharge current trough, the neutral population builds, and eventually the channel is left with slower ions that did not experience as large of a potential drop as the others. The cycle repeats as the discharge current ramps up again.

While the SPT-100 appears to have similar trends to this breathing mode model, the results are not nearly as pronounced as thrusters such as the BHT-600. In the BHT-600, variations in ion velocity in the ionization region inside the channel were as large as 15 km/s over a discharge current period with the peak intensity dropping to as low as 25% of its maximum, as opposed to the 75% seen in the SPT-100. The smaller intensity and velocity variations could be in part due to the smoothing induced by sampling with a $1 \mu\text{s}$ gate when the fluctuations in discharge current are $\pm 11.2 \mu\text{s}$. Further work is underway to quantify this smoothing factor.

Figures 13 and 14 show the time resolved ion velocities along the centerline of the thruster extending out to $Z = 80$ mm. Comparing the time resolved IVDFs in Fig. 13 to the time averaged in Fig. 8 we see that two distinct ion velocity populations exist between $Z = +10$ and 40 mm. While the higher velocity peak dominates, the lower velocity peak ebbs and flows in intensity, being most prominent as the thruster discharge current reaches its peak.

The corresponding radial measurements in Fig. 14 were unfortunately taken with fewer temporal points at most positions. The time resolved radial IVDFs are very noisy, as is expected from the broad, noisy time averaged velocity distributions seen in Fig. 9. Starting near the nose cone, the IVDFs grow in intensity, with wide flat distributions out until $Z = +60$ mm. Past this point, the radial double peak structure becomes more evident as the axial velocity peak becomes singular. The negative velocity peaks are slightly more prominent in the distributions between $Z = +60$ and $+80$ mm, which agrees with the time averaged measurements.

IV. Conclusions

This paper provides results of a CW-LIF velocimetry test campaign examining an SPT-100 Hall thruster. A full time averaged map of most probable ion velocity was presented for the discharge channel and near field plume of the thruster. IVDFs along the discharge channel and centerline of the thruster provided insight on the relative excited state ion populations in these regions, indicating the location of peak ionization in the discharge channel and a mixing region in the jet along the centerline of the thruster.

Time resolved measurements were then presented to further investigate the plasmadynamics of the thruster operation. Measurements were made using a sample-hold time synchronization method that cor-

relates fluorescence excitation lineshapes to the ~ 19.8 kHz breathing mode discharge current cycle of the thruster with $1\ \mu\text{s}$ resolution. Maps of most probable velocity at six different time points along a typical discharge current cycle revealed that the largest variations in ion velocities occurred in a turbulent region near the nose cone, extending out into a jet region along the centerline of the thruster. Both the magnitude and direction of ion velocity ebbed and flowed with the discharge current cycle, at some points showing multiple ion velocity populations particularly in the radial direction. Within the discharge channel, the time resolved measurements of the ionization and initial acceleration region followed a standard breathing mode pattern with the ionization front moving upstream in the channel as discharge current increases, followed by a peak in ion acceleration as the discharge current and measured fluorescence intensity fall back to their minima.

Overall, results for the SPT-100 followed measurements of other thrusters taken with this time resolved method of LIF velocimetry. The main difference seen in these results was the extent to which the fluorescence excitation lineshape intensity and most probable velocities varied over a discharge current cycle for points inside the discharge channel. The SPT-100 showed only slight variations in these properties, compared to several thrusters of 200-600 W class which virtually extinguished their excited state ion population during the acceleration phase of the breathing mode cycle.

V. Future Work

Several additional data sets were taken during this test campaign to examine different aspects of the SPT-100 thruster operation. These included measurements of azimuthal ion velocity, axial and radial ion velocities at varying operating conditions including different applied anode voltages and a range of chamber background pressures. Further analysis of this data is underway and will be presented at a future date.

Acknowledgments

This work is sponsored in part by the U.S. Air Force Office of Scientific Research with Dr. M. Kendra as program manager.

References

- ¹OKB Fakel. (2016) *100th SPT-100* [Press Release]. Retrieved from http://www.fakel-russia.com/index.php?option=com_content&view=article&id=127:presentation-by-loral&catid=56&lang=en&Itemid=198.
- ²C. Garner, J. Polk, K. Goodfellow, and J. Brophy. *Performance evaluation and life testing of the SPT-100: Proceedings of the 23rd International Electric Propulsion Conference & Exhibit*, Seattle, WA, September 13-16, 1993, IEPC-93-091.
- ³J. Sankovic, J. Hamley, and T. Haag. *Performance evaluation of the Russian SPT-100 thruster at NASA LeRC: Proceedings of the 23rd International Electric Propulsion Conference & Exhibit*, Seattle, WA, September 13-16, 1993, IEPC-93-094.
- ⁴M. Nakles, W. Hargus Jr., J. Delgado, and R. Corey. *A performance comparison of xenon and krypton propellant on an SPT-100 Hall thruster: Proceedings of the 32nd International Electric Propulsion Conference & Exhibit*, Weisbaden, Germany, September 11-15, 2011, IEPC-2011-003.
- ⁵M. Nakles, W. Hargus Jr., J. Delgado, and R. Corey. *A 205 hour krypton propellant life test of the SPT-100 operating at 2 kW: Proceedings of the 33rd International Electric Propulsion Conference & Exhibit*, Washington, DC, October 6-10, 2013, IEPC-2013-347.
- ⁶D. Pidgeon, R. Corey B. Sauer, and M. Day. *Two Years On-Orbit Performance of SPT-100 Electric Propulsion: Proceedings of the 24th International Communications Satellite Systems Conference*, San Diego, CA, June 11-15, 2006, AIAA-2006-5353.
- ⁷R. Corey and D. Pidgeon. *Electric Propulsion at Space Systems/Loral: Proceedings of the 31st International Electric Propulsion Conference & Exhibit*, Ann Arbor, MI, September 20-24, 2009, IEPC-2009-270.
- ⁸S. Kim and A. Gallimore. *J. Spacecraft Rockets* **39** 6 (2002).
- ⁹L. King and A. Gallimore. *J. Propul. Power* **16** 5 (2000).
- ¹⁰L. King and A. Gallimore. *J. Propul. Power* **14** 3 (1998).
- ¹¹k. Kwon, M. Walker, and D. Mavris. *Plas. Sources Sci. Technol.* **20** 045021 (2011).
- ¹²R. Myers and D. Manzella. *Stationary plasma thruster plume characteristics: Proceedings of the 23rd International Electric Propulsion Conference & Exhibit*, Seattle, WA, September 13-16, 1993, IEPC-93-096.
- ¹³D. Manzella and J. Sankovic. *Hall thruster ion beam characterization: Proceedings of the 31st AIAA / ASME / SAE / ASEE Joint Propulsion Conference*, San Diego, CA, July 10-12, 1995, AIAA-95-2927.
- ¹⁴U. Lebedev, G. Popov, and V. Zhurin. *Measurement of plasma parameters in the Stationary Plasma Thruster (SPT-100) plume and its effect on spacecraft components: Proceedings of the 28th Joint Propulsion Conference & Exhibit*, Nashville, TN, July 6-8, 1992, AIAA-92-3156.

- ¹⁵E. Pencil *Preliminary far-field plume sputtering of the Stationary Plasma Thruster (SPT-100): Proceedings of the 23rd International Electric Propulsion Conference & Exhibit*, Seattle, WA, September 13-16, 1993, IEPC-93-098.
- ¹⁶E. Pencil, T. Randolph, and D. Manzella *End-of-life Stationary Plasma Thruster far-field plume characterization: Proceedings of the 32nd AIAA / ASME / SAE / ASEE Joint Propulsion Conference*, Lake Buena Vista, FL, July 1-3, 1996, AIAA-96-2709.
- ¹⁷D. Manzella *Stationary plasma thruster plume emissions: Proceedings of the 23rd International Electric Propulsion Conference & Exhibit*, Seattle, WA, September 13-16, 1993, IEPC-93-097.
- ¹⁸D. Manzella *Stationary plasma thruster ion velocity distribution: Proceedings of the 30th AIAA / ASME / SAE / ASEE Joint Propulsion Conference*, Indianapolis, IN, June 27-29, 1994, AIAA-94-3141.
- ¹⁹J. E. Hansen, and W. Persson. Phys. Scr. **4**, 602 (1987).
- ²⁰N. A. MacDonald, C. V. Young, M. A. Cappelli and W. A. Hargus Jr. J. Appl. Phys. **9**, 093303 (2012).
- ²¹Hargus, Jr., W. A. and M. A. Cappelli. Appl. Phys. B **8**, 961 (2001).
- ²²S. Mazouffre, D. Gawron, V. Kulaev, and N. Sadehgi. IEEE Trans. Plasma Sci. **36**, 1967 (2008).
- ²³W. Hargus Jr. and M. Nakles IEEE Trans. Plasma Sci. **36**, 5 (2008).
- ²⁴M. H. Miller, and R. A. Roig. Phys. Rev. A **8**, 480 (1973).
- ²⁵A. Kramida, Y. Ralchenko, J. Reader, and NIST ASD Team *NIST Atomic Spectra Database (ver. 5.2):<http://physics.nist.gov/asd> [2015, May 15]*, National Institute of Standards and Technology, Gaithersburg, MD., 2014.
- ²⁶N. MacDonald-Tenenbaum, C. Young, A. Lucca Fabris, M. Nakles, W. Hargus Jr. and M. Cappelli *Time-Synchronized Continuous Wave Laser Induced Fluorescence Velocity Measurements of a 600 Watt Hall Thruster: Proceedings of the 34th International Electric Propulsion Conference* Hyogo-Kobe, Japan, July 4-10, 2015, IEPC-2015-350.
- ²⁷N. A. MacDonald, M. A. Cappelli, and W. A. Hargus Jr. Rev. Sci. Instrum. **83**, 113506 (2012).
- ²⁸A. Lucca Fabris, C. V. Young and M. A. Cappelli Plasma Sources Sci. Technol. **24**, 055013 (2015).
- ²⁹M. Scharfe, N. Gascon, and M. Cappelli Phys. of Plas. **13**, 8 (2006).
- ³⁰F. Parra, E. Ahedo, J. Fife, and M. Martinez-Sanchez J. Appl. Phys. **100**, 2 (2006).
- ³¹C. V. Young, A. Lucca Fabris and M. A. Cappelli Appl. Phys. Lett. **106**, 044102 (2015).
- ³²A. Lucca Fabris, C. V. Young and M. A. Cappell J. Appl. Phys. **23**, 233301, (2015).
- ³³N. A. MacDonald, M. A. Cappelli and W. A. Hargus Jr. J. Phys. D (11), 115204, (2014).
- ³⁴J. P. Boeuf and L. Garrigues J. Appl. Phys. **84**, 3541 (1998).
- ³⁵S. Barral and E. Ahedo Phys. Rev. E **79**, 046401 (2009).

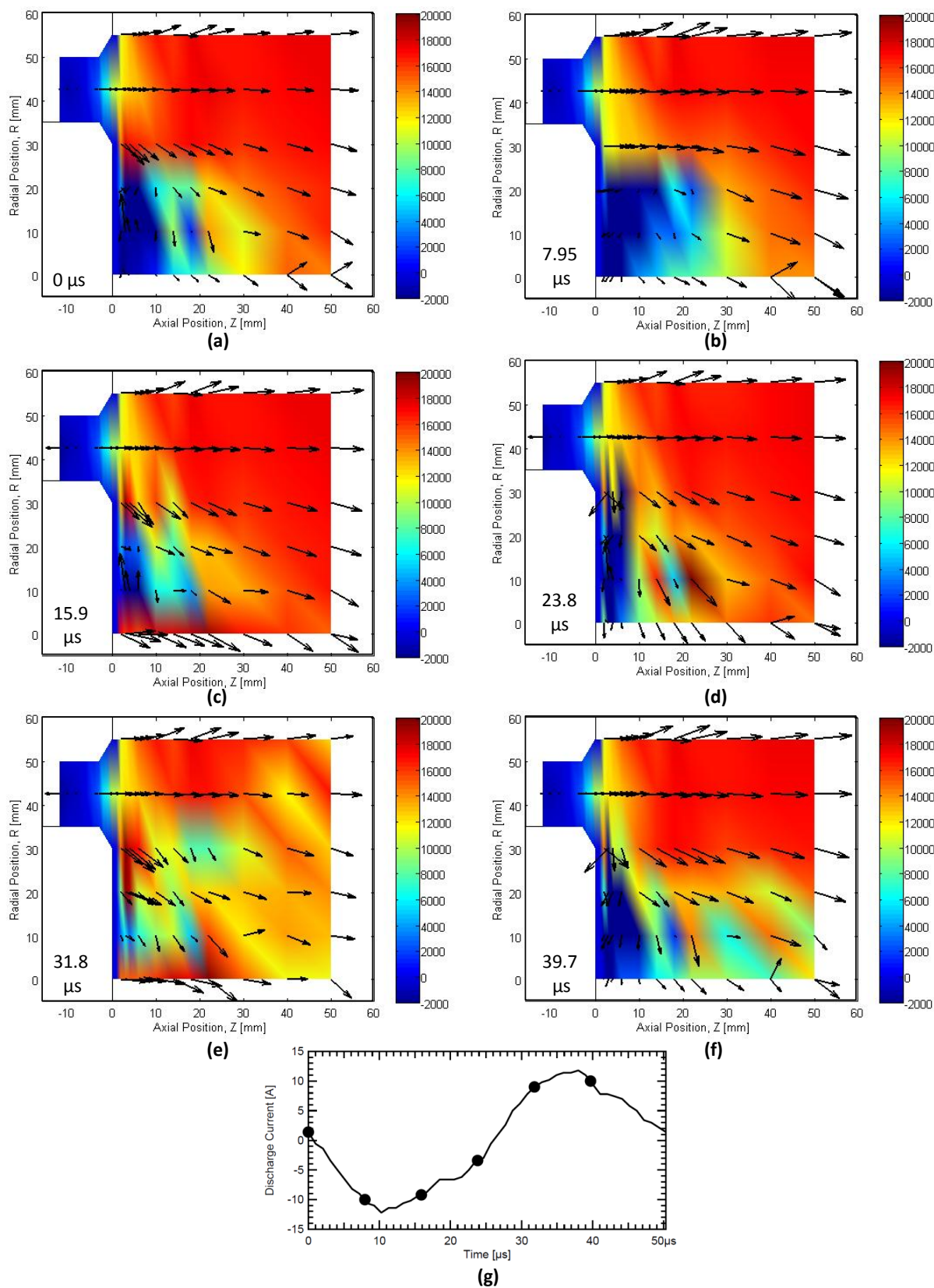


Figure 10. Time resolved most probable ion velocities in the discharge channel and near-field plume of the SPT-100 Hall thruster. Arrows indicate the direction of ion flow. Images correspond to (a) $t = 0 \mu s$, (b) $t = 7.95 \mu s$, (c) $t = 15.9 \mu s$, (d) $t = 23.8 \mu s$, (e) $t = 31.8 \mu s$, and (f) $t = 39.7 \mu s$ along a typical discharge current cycle, as shown in (g).

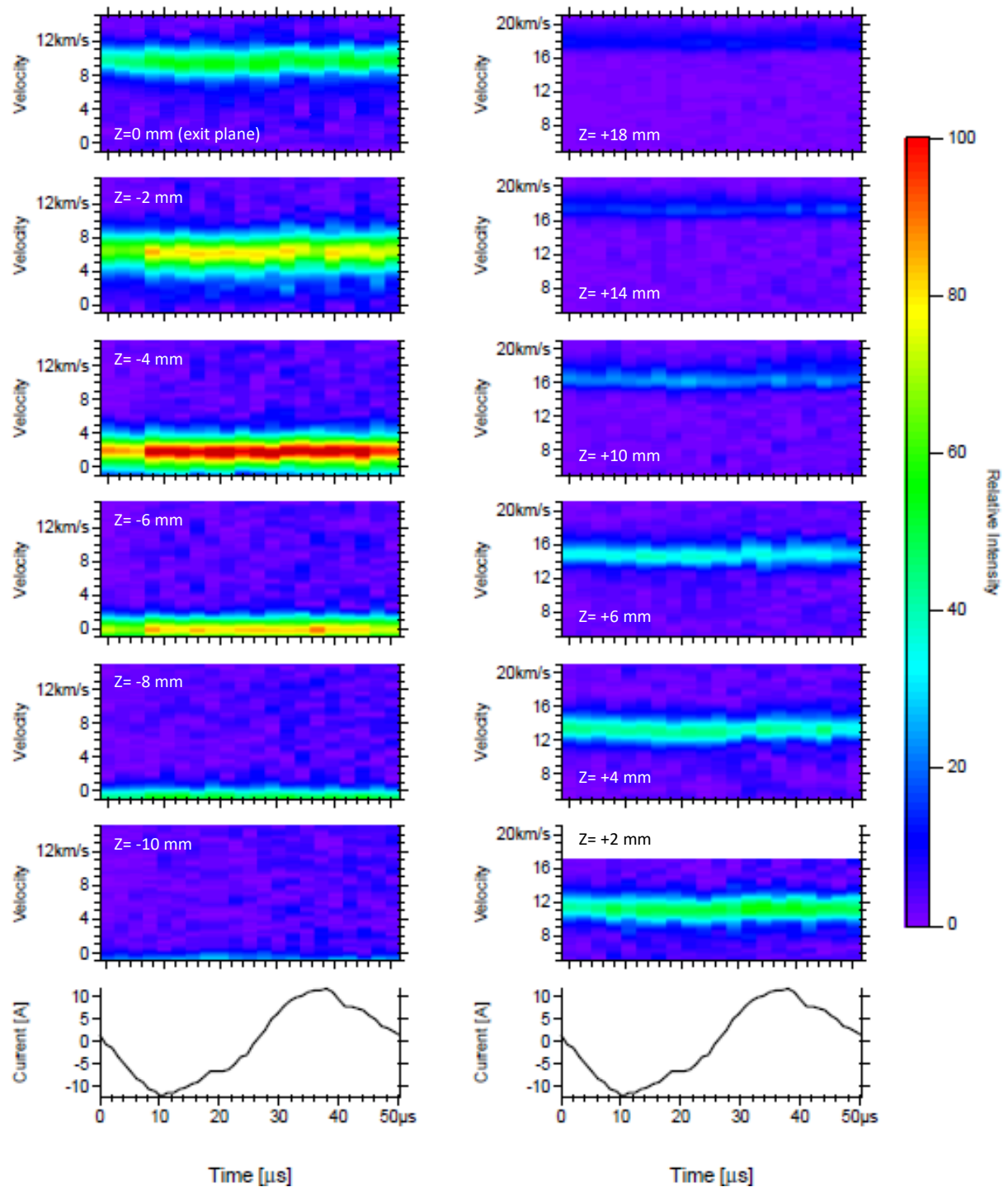


Figure 11. Time resolved axial ion velocities at $R=42.5$ mm over a discharge current period. Left side of figure depicts ionization and acceleration region inside the thruster channel. Right side of figure depicts velocities continuing into the near-field plume Note: All positions are normalized to the maximum intensity of the measured fluorescence excitation lineshape that occurred at $Z=-4$ mm.

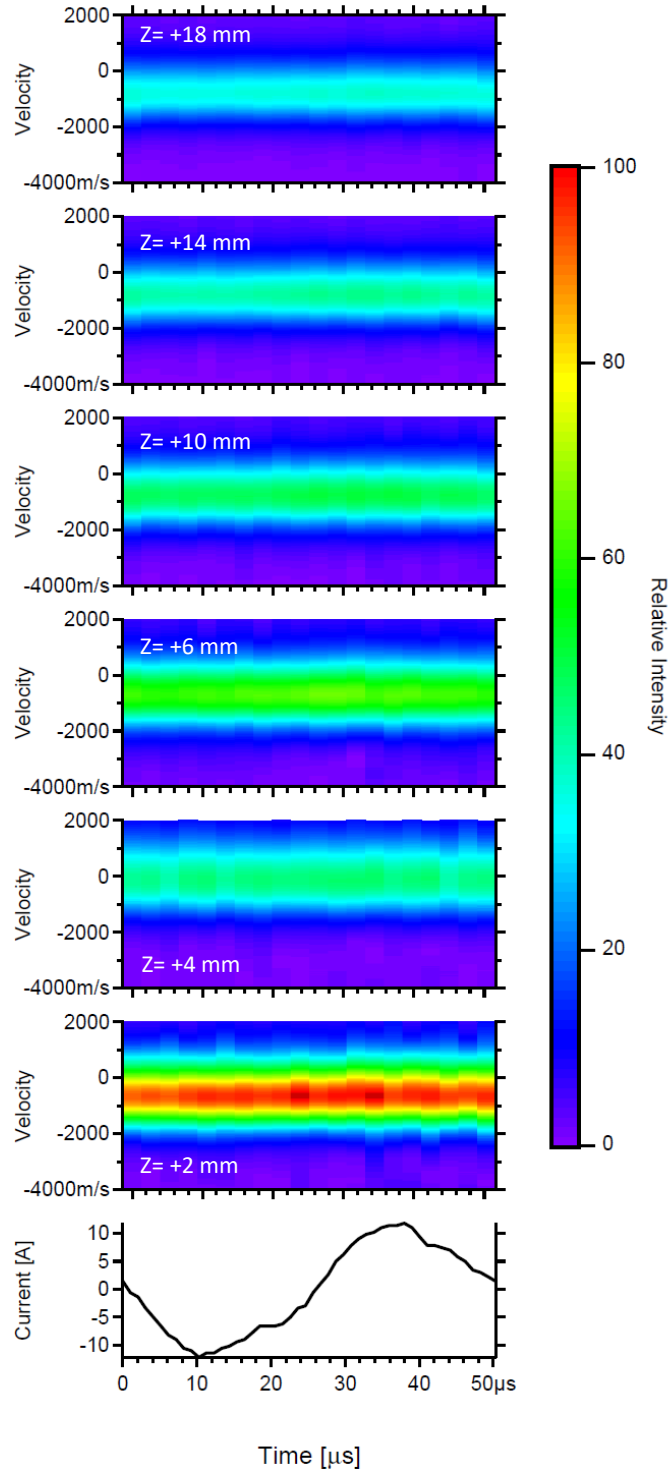


Figure 12. Time resolved radial ion velocities at $R=42.5$ mm over a discharge current period.

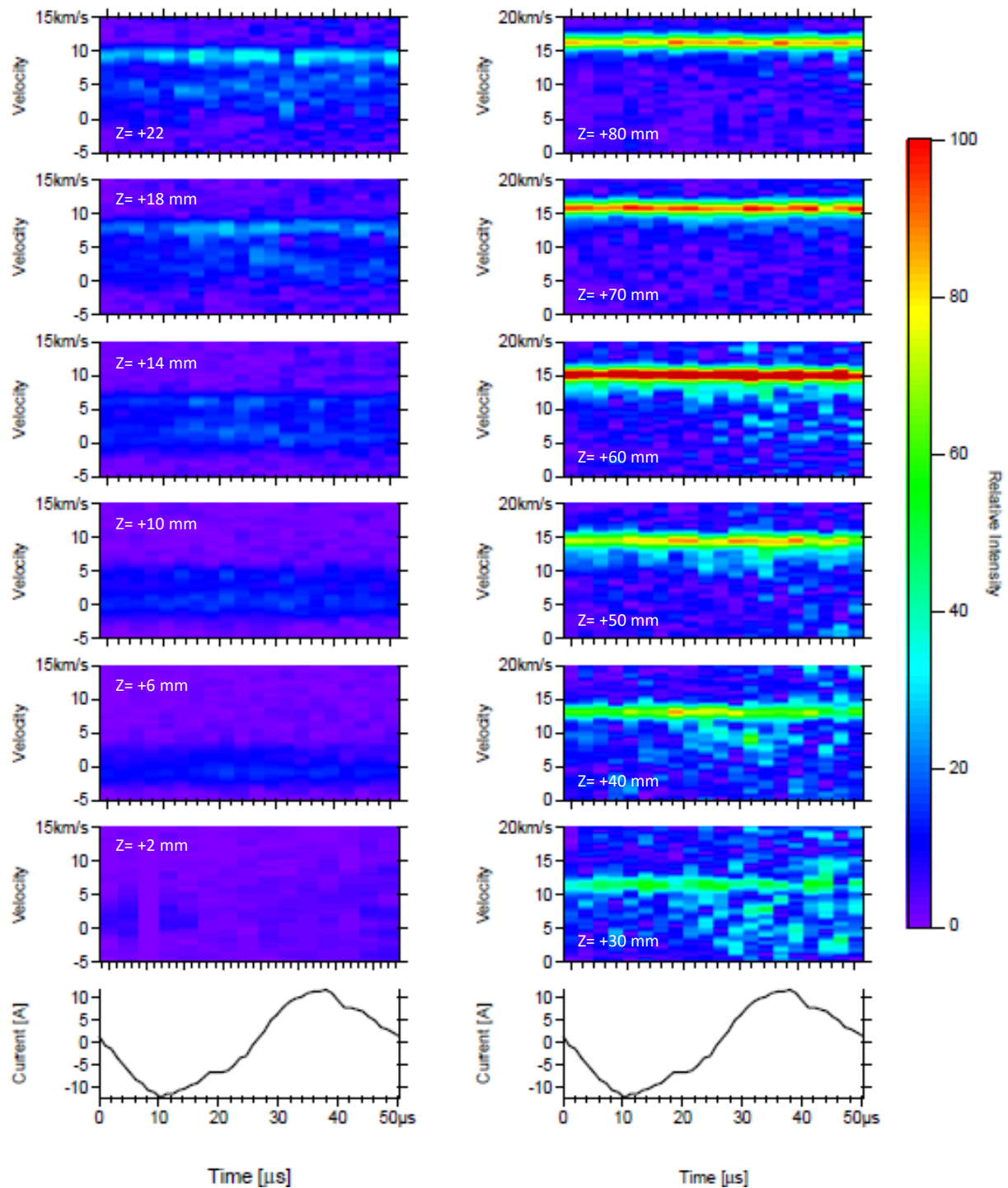


Figure 13. Time resolved axial ion velocities at $R=0$ mm along the centerline of the thruster over a discharge current period. Left side of figure depicts Near the thruster nose cone out to $Z=22$ mm. Right side of figure depicts velocities continuing out to 80 mm in the near-field plume Note: All positions are normalized to the maximum intensity of the measured fluorescence excitation lineshape that occurred at $Z=2$ mm.

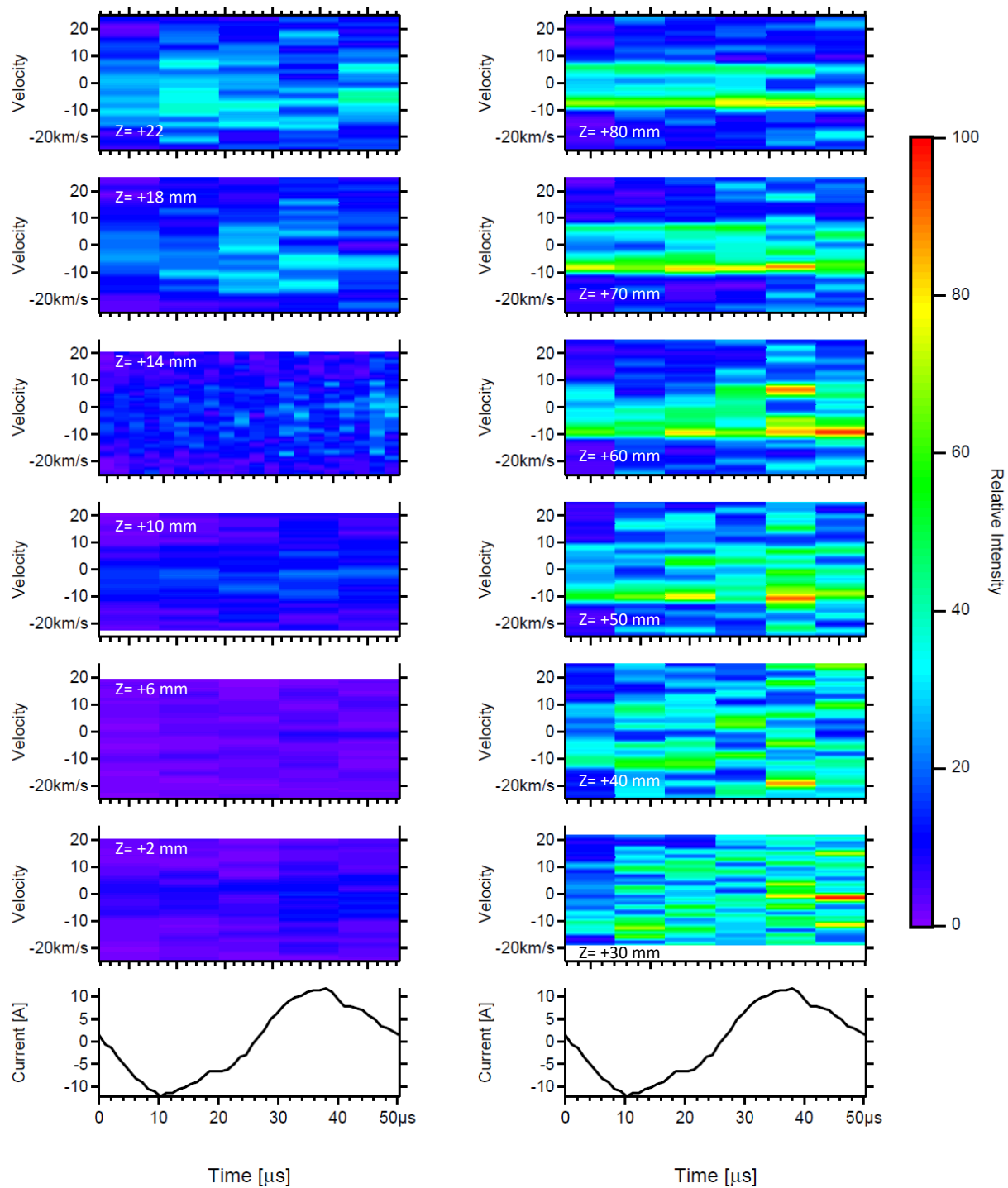


Figure 14. Time resolved radial ion velocities at $R=0$ mm along the centerline of the thruster over a discharge current period. Left side of figure depicts Near the thruster nose cone out to $Z=22$ mm. Right side of figure depicts velocities continuing out to 80 mm in the near-field plume Note: All positions are normalized to the maximum intensity of the measured fluorescence excitation lineshape that occurred at $Z=2$ mm. The time resolved radial IVDFs were taken with fewer temporal points at most positions (5-6 instead of 20), but have the same resolution in velocity space (60,000 points).