

Electric Thruster Ingestion and Background Propellant Density Measurements

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Abstract: High pumping speed and low facility interactions are critical design goals for electric propulsion test facilities, to better simulate the space environment and adequately evaluate electric thrusters. Using multiple ion gauges at various points inside a test facility, and a highly accommodative internal buffer chamber, comparison between hot and cold flow data demonstrates that flow dynamics inside the test facility are more complex than has generally been realized. It shows that “standard” ways of measuring pressure are inadequate for determining the propellant ingestion rate of operating electric thrusters because they do not measure flux, and that hot and cold flow ingestion rates are not the same. The assumption made repeatedly in the past - that energetic ions and neutrals are completely accommodated to the local surface temperature after a single collision with that surface - is false. Understanding the physics is required to better characterize thrusters during ground tests and improve in-space performance predictions.

I. Motivation and Background

The simulation of space conditions in ground test facilities cannot reproduce the high vacuum typically encountered by spacecraft in Earth orbit. This is because of pumping speed limitations. Due to the relatively high background density of propellant gas stemming from the exhaust of an ion propulsion device that has not been pumped away, interactions with an operating electric thruster modify ground test behavior and create a deviation relative to in-space behavior. [1-17] For a Hall Effect thruster operating under low pressure conditions the effective ionization volume becomes more extended, divergence increases, plume potential elevates, thrust level decreases, erosion rate and lifetime changes, and propellant flow rate must be raised to maintain a given beam current level. These effects are typically not the same in different ground test facilities, varying with facility geometry and vacuum pump placement and speed. Single or perhaps dual spot measurements of pressure or density are routinely performed, usually with a Bayard Alpert type of ionization gauge mounted to chamber wall, to help document facility conditions. However, these do not reveal density distribution or flow dynamics of background propellant gas inside the vacuum chamber, and do not provide adequate information to accurately quantify the rate of gas ingestion by an operating thruster. Gauges installed inside the test chamber provide better insight, but their usage has been infrequent and unstandardized. [3-5, 9-11]

When a gas particle collides with a smooth surface at low to moderate temperature there are two main ways it can come away. It can undergo a reflection that is nearly specular, with little energy loss, or depart with largely random direction and reduced velocity that correlates with the surface temperature. This concept of the energy accommodation coefficient originated in the 19th century [18] and was further developed by Knudsen in the early 20th. The thermally randomized case is believed to arise from physisorption and subsequent desorption with cosine angular distribution, whereas specular reflection involves no trapping and produces a narrow angular distribution around the specular direction. For heavy rare gases like xenon and most surfaces, classical physics provides good results and quantum mechanics is not required. [19]

There is existing experimental [3,4] and theoretical [20-23] evidence that directional gas flow inside the facility can be an influential factor during thruster operation, and under cold flow conditions as well. This

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happens because the thruster generates a virtual distributed gas source around the downstream end of the chamber, and each cryopump continuously sinks exhaust propellant to create a low-density environment around it. The density gradient that is established often puts the thruster well below peak chamber density and potentially in position to intercept the directional flow. This situation only requires the thruster to flow gas, not to operate. If all pumps are located just behind the thruster this gradient will tend to be maximized, whereas if they are entirely located downstream the thruster will likely see reduced directional flow. [23] With increased pumping speed comes the potential for higher density gradient and enhanced directional flow. With high sticking coefficient and large pump area generating high pumping speed, average flow velocity may become a significant fraction of the mean velocity corresponding to a Maxwell-Boltzmann (thermalized) distribution, making it no longer zero-based. [20] When flow is directional with significant velocity the particle flux across a surface perpendicular to the flow direction is increased.

Only recently has it been hypothesized that average flow velocity in an ion propulsion test facility may be elevated well above the mean thermal velocity. [23,24] Studies of facility effects in electric propulsion test chambers almost universally assume that beam ions encountering a beam stop, wall or cryogenic surface come away as a neutral with perfectly thermalized energy. [1-11] Allowable background pressure limits were proposed decades ago, [2] based on this assumption and others, and later found to be invalid. Ingestion rates calculated on this basis were found insufficient to explain observed results and various additional explanations for observed behavior were then invoked. Revised standards for pressure measurement were since proposed and largely adopted by the community, but they do not account for directional flow and its potential implications. [25] However, it has been known for more than three decades that beam ions typically retain most of their kinetic energy for collisions at high angle of incidence and retain a much smaller percentage when impinging with low angle of incidence – nevertheless leaving the neutrals with hyperthermal velocity. The outgoing kinetic energy depends on several factors, including incoming ion energy and mass, surface composition and constituent mass, presence of adsorbed impurity (or adsorbed/implanted beam particles), angle of incidence, surface temperature and so on. One method of producing an intense, energetic neutral beam is to shoot a beam of ions at a suitable surface at near grazing incidence. [26,27] Hyperthermal neutral species impinging on a surface produce a similar result. The likelihood of specular reflection events tends to go up with increasing particle energy and mass, whether ion or neutral, as well as decreasing mass of atoms in the metal. The extent to which a colliding particle is thermalized is quantified by the accommodation coefficient, which can be defined as [19]

$$\alpha = \frac{E_i - E_f}{E_i - E_s}, \quad (1)$$

where E_i is the initial gas particle kinetic energy, E_f is the final gas kinetic energy after collision with the surface and E_s is the gas kinetic energy if it departs from the surface fully thermalized. In other words, α is the ratio of actual ΔE to maximum possible ΔE for the collision. Nearly all electric propulsion analytical and simulation studies take α to be unity, a poor assumption in many cases. It is not unusual that α for relatively low velocity collisions of neutral species on surfaces at room temperature is 10-20% lower than unity. [19,28]

As a result, the real rate of thruster gas ingestion can be much higher than calculated based on traditional assumptions of random velocity distribution at wall temperature. Here we define rate of ingestion as the rate particles cross the exit plane of the thruster and enter the discharge chamber. This elevated rate, which was unappreciated by many facility effects studies, has meant that pressure (or density) measurements and conclusions drawn from them about rate of thruster ingestion and facility pumping speed are typically inadequate and misleading. The practice of measuring pressure with an ion gauge at the vacuum chamber wall, with little attention given to its specific location with respect to thruster position and facility geometry, and assuming uniform conditions throughout the facility (except in the flowfield near the thruster exit), was typical for many years. The method has become more standardized, with axial location specified to coincide with thruster exit plane. [25] The use of internal ion gauges in a multi-directional, multi-position measurement configuration is rare.

II. Approach

Pressure measurements were performed inside the EP3 electric propulsion vacuum test chamber at The Aerospace Corporation. Due to the novel design of its cryopumps EP3 currently has the highest pumping speed of any dedicated electric propulsion test facility. [29-31] It is a 427-cm diameter (14 feet), approximately 10-m (33 feet) long cylindrical stainless steel facility with end caps and five cryopump “rings”, as shown in Fig. 1. One of these rings, located near the ion beam stop at the door end, is made up of six TM-1200i re-entrant PHPK pumps. The other four rings are of custom Aerospace design, were constructed by GNB Corporation, and are intended to provide very high pumping speed. The beam stop covers the downstream dome and a large gate valve is attached to the upstream dome. On the other side the gate valve connects to a fiberglass chamber inside a semi-anechoic room for EMI measurements, so that the pumping capacity of the main chamber can be utilized. An electric thruster is typically installed either in the fiberglass chamber or inside the main chamber, which was the location for the present study. Except for the end domes, the ~75-cm wide “thruster gap” region where the thruster was installed, and smaller gaps between cryopump rings, chamber wall is covered with aluminum panels cooled by flowing liquid nitrogen. In the thruster gap and gaps between cryorings most of the area is covered by thermal gap shields – 6063 T5 aluminum plate segments that are thermally connected to LN2-cooled sheet on one or both sides. Peak gap shield temperature is closer to LN2 boiling point than chamber wall temperature. Individual plates are removed or have apertures cut in them to accommodate vacuum feedthroughs, windows, and so on. In addition, the chamber walkway is thermally isolated and has an LN2 cooling loop. Cryogenic helium lines are wrapped in thermal insulation. The thruster gap platform on which thrusters are mounted is thermally connected to chamber wall through its support legs, limiting the temperature swing during chamber operations. For the present study three of the six TM-1200i pumps were always operating, together with 0 to 4 of the custom rings. The custom rings consist of 7 interconnected pumps, each having a helium panel sandwiched between the LN2 panel on the chamber wall side and LN2-cooled chevron assembly on the “inside”. Each custom ring has an octagonal arrangement, with the bottom (eighth) position occupied by an LN2 panel installed under the walkway – without chevron or helium panel. The helium panels pump from the wall side in addition to through the chevrons, as there is adequate separation from the LN2 panel to permit propellant to readily access the back side. The helium panels are cooled by cryogenic gaseous helium fed from a Linde RSX compressor/model 1620 refrigerator system, with up to 22 gram/s total helium flow rate at 20K that can be apportioned between the rings. Individual helium panel dimensions are approximately 130 × 121 cm each, with 28 panels in total, made of 6063-T5 aluminum. Since the cryopumps are ineffective on hydrogen and helium, a turbopump is normally running to ensure low background pressure for these gases. All data for the present study were obtained with cold chevrons and LN2 panels, regardless of whether helium panels were operative for pumping the xenon propellant, except for a single PHPK-only hot flow case. Further details about the facility design are available. [29-30]

A pair of low power Hall thrusters was mounted on the platform in the thruster gap region (see Fig. 2). They are distinguished by the labels RH (right hand) and LH (left hand). Cold flow measurements were obtained mainly with the RH thruster, over the 0 – 50 sccm flow range, with a more limited LH data set for comparison. Hot flow measurements were performed with both thrusters on at nominal discharge settings of 0.93 Ampere and 300 Volts, and about 28 sccm total flow rate of research grade xenon propellant split equally between the thrusters. Cathode flow rate was 10% of the total.

An internal Stabil-Ion gauge attached to 90-degree elbow was installed at the midpoint below the thruster pair, with meshed entrance aperture approximately at the thruster exit plane and facing the downstream direction. This has been a standard configuration at Aerospace for internal pressure measurement, although typically mounted off to the side and not at the same distance from the thruster in every case. We will refer to pressure data from this setup as standard internal or simply internal.

A sphere of approximately 23 cm diameter with two ports in the horizontal plane served as the accommodation chamber (see Fig. 2). One port was blanked off and the other faced downstream, with a fine mesh covering. A Stabil-Ion gauge mounted on top was used to obtain the pressure (density) measurements. The chamber, by virtue of its geometry, ensured that admitted gas was well accommodated to its wall temperature. A rotational stage was later positioned underneath to vary the viewing direction, but it was not functional for the present study. Use of a spherical geometry assures multiple wall collisions will be experienced by an entering gas particle prior to

encountering the ionization volume inside the pressure gauge. Other chamber designs may produce inaccurate density data if gas does not fully equilibrate to the vessel wall temperature, producing nonuniform internal density and temperature. This is more likely to occur if the velocity vector for gas near the entrance port has preferred directionality, with average speed comparable to or higher than pertains to the Boltzmann distribution, and the geometry allows gas to reach the ionizer or exit the chamber after few or no wall collisions.

There were five ion gauges in total for this study, four internal and one wall-mounted. All internal gauges were of the Stabil-Ion type, and each was wired to a vacuum feedthrough. Cables were shielded to reduce noise pickup, except for the gauge furthest downstream which viewed the beam stop/chamber door. Each inlet port had a mesh screen, which was the manufacturer-supplied article for dome-view (see Fig. 2) and wall-mount gauges. The Debye length for all devices was larger than the mesh size, due to the low-density of plasma in their vicinity. The standard internal and thruster-view gauges had a 90-degree elbow attached for added protection from the plasma environment. A heater was attached to the case of each internal ion gauge, except the one at the wall. All gauge temperatures are therefore assumed to be room temperature (thermocouple readings indicated the internal gauges were at this temperature or slightly below). Since the dependence goes with square root of temperature their output should be in reasonable agreement with calibration results obtained at room temperature. [25,32-33] It was discovered during the study that heater operation affected some of the ion gauges, especially the downstream gauge viewing the end dome/door, creating a significant offset. The measurement error was especially troublesome at low pressure. The wall-mounted gauge was a Kurt Lesker device, with integrated electronics. The “standard internal” gauge mounted closest to the thruster pair and attached to a 90-degree elbow, is consistent with the configuration we have used often in the past. The pair of downstream ion gauges was aligned radially with the left side thruster but somewhat below its height, to maintain good visibility from the end dome viewport. Pressure readings were recorded manually for some initial data sets, then electronic logging was implemented for sphere and standard internal data. In all cases the reported pressure or density is for xenon, corrected for ion gauge sensitivity after subtracting the baseline reading with no xenon flowing. Baseline gauge readings were typically in the low 10^{-8} torr range for sphere and standard internal, 10^{-7} range for thruster view, and low 10^{-6} range for dome-view.

The ionization gauges perform a measurement of gas density and convert that to a pressure reading, using a sensitivity factor. If temperature decreases inside the ionization region the gas density there will increase, and the reading will increase in accordance with the density. Therefore, it is useful to maintain each gauge at the same, constant temperature and to have knowledge concerning the gas temperature in each existing environment. Consider the case in which the ionization gauge is separated from the main facility by a small chamber that ensures plasma and gas particles have no line of sight to the gauge, and two different gas temperatures exist inside the chamber and outside in the background (facility) gas. The flux into the small internal chamber will be proportional to the product of external gas density and square root of external temperature, and the flux out will be proportional to the product of internal gas density and square root of internal temperature. Equating the two we have

$$n_e \sqrt{T_e} = n_i \sqrt{T_i}, \quad (2)$$

where subscripts e and i refer to external and internal, respectively. If the internal and external temperatures are known and the internal density is determined from the ionization gauge measurement, the external density can be obtained from this relation.

If the spherical chamber and ion gauge system moves through thermalized background gas at significant velocity, such as a spacecraft moving through tenuous atmosphere, the flux balance equation becomes [34]

$$e \sqrt{T} \{ e^{-S^2} + S \sqrt{\pi} [1 + \text{erf}(S)] \} = n_i \sqrt{T_i}, \quad (3a)$$

where S is given by

$$S = \frac{|v| \cos(\alpha)}{\sqrt{\frac{2kT_e}{m}}}. \quad (3b)$$

Here k is Boltzmann's constant and m is propellant (xenon neutral) mass. For $S \geq 3$, Equation 3 can be approximated to yield

$$n_e \sqrt{\frac{2\pi m}{k}} |\mathbf{v}| \cos(\alpha) = n_i \sqrt{T_i} . \quad (4)$$

Here the external (outside) temperature, which may not be well-known, no longer appears. Therefore, if the internal density and temperature are measured, and the speed and angle of attack are known, the external density can be calculated. Conversely, if the external density near the spherical chamber entrance is known, the quantity $|\mathbf{v}| \cos(\alpha)$ can be calculated. However, the situation is more complicated than this formalism allows. Our assumption is that the external (facility) gas has a substantial directed velocity that is superimposed on a relatively zero-based Maxwellian (thermalized) distribution. We therefore treat our facility gas as two distinct components, such that the external density is given as

$$n_e = n_{re} + n_{de} , \quad (5)$$

where n_{re} and n_{de} are the thermalized (random) and directed flow densities of the external (facility background) gas, respectively. The thermalized component is governed by the Maxwell-Boltzmann distribution. The directed component is due primarily to beam ions that were converted to atoms in the downstream region, returning to the vicinity of the thruster before they have been fully thermalized. They are directional in part because beam ions were launched in the downstream direction, with a substantial fraction – depending on beam divergence – even reaching the far wall of the facility. As a result, the downstream end of the facility sources a flow of neutral xenon atoms that move upstream toward the thruster. Those that encounter the cryogenic pumping surfaces along the side wall may be pumped away, or partially/fully accommodated to the thermal environment before reaching the thruster. Those atoms which are not pumped away and experience no collisions before they encounter the thruster contribute to the directional density in Equation 5. Atoms which experience one or more high angle surface collisions before encountering the thruster as they move further upstream may also be directional with reduced average velocity, and still contribute to the directional density and flux. The thermalized component has been accommodated to the chamber environment via collisions and does not have a significant directional bias. If the entrance of our internal chamber points upstream we can consider it to sample only thermalized gas, and when the entrance points downstream it sees both thermalized and directed.

The contribution of external thermalized atoms to the internal density can be found from Equation 2, written as

$$n_{ri} = n_{re} \sqrt{\frac{T_e}{T_i}} , \quad (6)$$

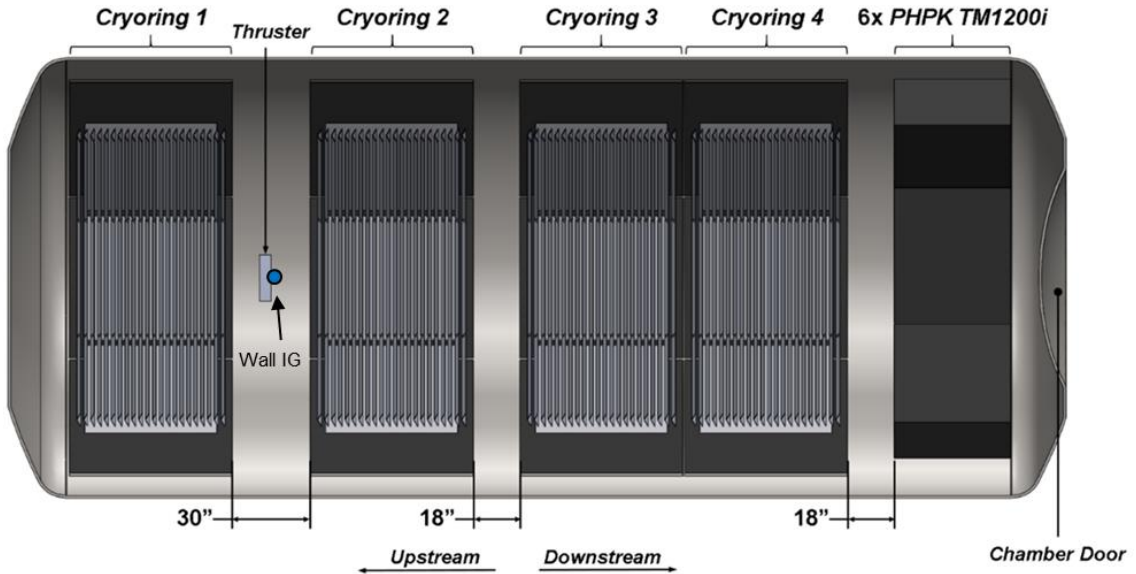


Fig. 1 Diagram of EP3 main chamber, showing locations of pumping rings.

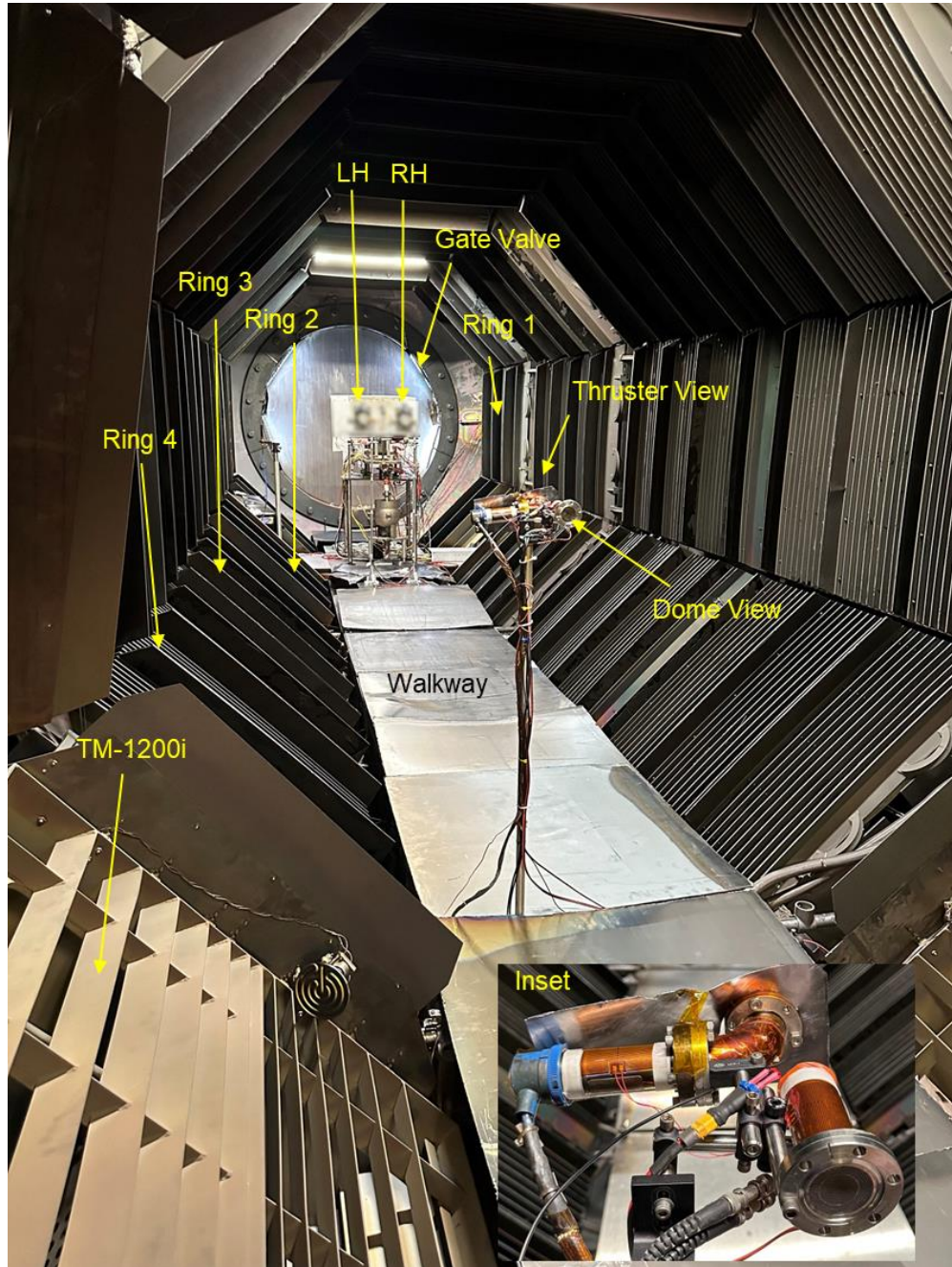


Fig. 2 Annotated photo of overall setup in the EP3 test facility. The inset photo provides more detail for the downstream ion gauges; one views the thrusters and the other views the end dome and ion beam stop. Wall mounted gauge is in the thruster gap region and not visible here. The gate valve on the upstream dome is closed.

where the ri and re subscripts refer to random internal and random external, respectively. The velocity of thermalized atoms is given by

$$v_r = \sqrt{\frac{8kT}{\pi m}}. \quad (7)$$

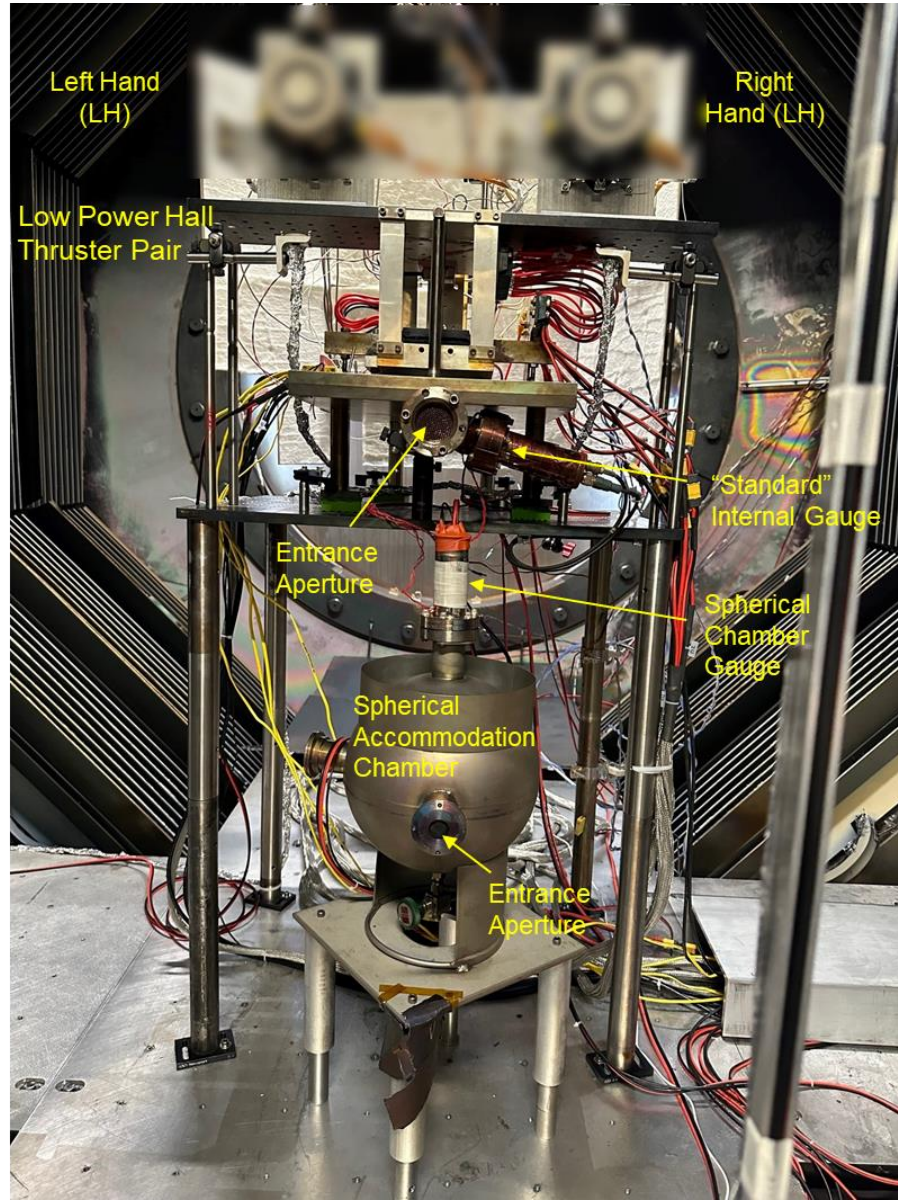


Fig. 3 Photo of the spherical accommodation chamber with its ion gauge, "standard" internal ion gauge, and pair of low power electric thrusters mounted above.

Writing directed flux as the product of directed density and effective velocity, and random flux as the product of thermalized density and mean Maxwell-Boltzmann velocity divided by 4, then equating inward and outward flux for the internal chamber yields

$$n_{re} \sqrt{\frac{T_e}{T_i}} + n_{de} \sqrt{\frac{2\pi m}{kT_i}} v_d \cos \alpha = n_i. \quad (8)$$

Here $n_i = n_{ri} + n_{di}$. Note that this result is identical to Equation 4, except that it includes the contribution of external thermalized gas to internal chamber density.

The ionization gauge is a density detector that normally provides a pressure reading. The relationship between density and pressure for the gauge reading is affected by temperature, which is typically not known with precision.

From the ideal gas law,

$$P = nkT \quad . \quad (9)$$

The temperature inside the ion gauge is affected by power dissipation from the heated filament which supplies the electrons for ionizing gas inside the envelope. Atoms or molecules in the external gas, with a complex velocity distribution determined by facility interactions after they are expelled from a thruster, cannot be assumed to have a well-defined temperature. For an ion gauge mounted to an intermediate chamber which the facility gas must navigate to reach it, the temperature will be well defined at its entrance aperture if the intermediate chamber is of appropriate geometry and its temperature is monitored. The pressure and density in the ionization volume will differ from the intermediate chamber volume, in the general case. If temperatures are stable and an equilibrium situation applies, the flux into the gauge will equal the flux out and

$$n_i \sqrt{T_i} = n_g \sqrt{T_g} , \quad (10)$$

where the subscript g refers to the ion gauge. Using Equation 9, we can rewrite in terms of pressure and temperature to obtain

$$P_i = P_g \sqrt{\frac{T_i}{T_g}} . \quad (11)$$

Density decreases with square root of temperature and pressure increases with square root of temperature, at constant volume. These relations still work if there is an intermediate chamber; the two “outside” temperatures are all that is needed, since the intermediate temperature will cancel out. In our case there is an external environment, intermediate chamber, and ion gauge ionization region as the third environment. Each of the three temperatures may differ, and if there is indeed a directed velocity component in the external environment the temperature there is essentially undefined. Therefore, it is necessary to subtract the contribution of that directed velocity component from the ion gauge reading before applying the temperature scaling relations.

The directed flow contribution to the spherical ion gauge pressure has been calculated for numerous cases and listed in Table I together with the random and directed density components, and ingestion rate elevation. We assume thermalized density of $5E+10 \text{ cm}^{-3}$ and 155K temperature in the external environment, various values for the directed velocity, and 290K ionization gauge temperature (close to the calibration temperature so no additional correction to the reading was made). To obtain the density elevation of the ion gauge measurement due to directed external flow we apply the relation

$$n_{dg} = n_g - n_{re} \sqrt{\frac{T_e}{T_g}} . \quad (12)$$

The measured density in the gauge, n_g , is made up of directed (n_{dg}) and random (n_{rg}) components. The contribution of external directed flow to the external density is then obtained (see Equations 4, 8) from

$$n_{de} = n_{dg} \sqrt{\frac{kT_g}{2\pi m}} / (v_d \cos \alpha) . \quad (13)$$

The ingestion ratio is

$$(n_{de} v_d \cos \alpha + \frac{n_{re} v_{re}}{4}) / (\frac{n_{re} v_{re}}{4}) . \quad (14)$$

The value of $\cos \alpha$ was assumed to be 0.9. The ingestion ratio varies up to about 8 for the selected parameters and increases linearly with the difference between total density in the spherical ion gauge and the thermalized density component in the external facility environment. If the gauge on the spherical chamber sees density $3 \times$

higher than the thermalized contribution in the facility the calculated ingestion rate is $4.1\times$ higher than expected for randomized behavior. We can directly apply the ratio between the spherical and wall-mounted gauges to estimate the real ingestion rate, since both are roughly at room temperature. Applying the Loschmidt number to relate pressure and density on an absolute basis, we take $3.4\times 10^{11} \text{ cm}^{-3}$ as the density that corresponds to a reading of 1×10^{-5} torr for both wall-mounted and spherical chamber gauges.

These results suggest that the actual ingestion rate is much higher than the rate obtained when complete thermalization is assumed. The directed flow component, although its contribution to external density is not large, can cause a substantial increase to the flux crossing the thruster exit plane in the upstream direction and corresponding increase of the ingestion rate. However, ion-neutral scattering is a potential impediment to this process. More powerful Hall thrusters produce ion beams of greater intensity, and the rate of ion-neutral scattering can be substantial, helping to counter the effect of high background density that results from relatively high propellant flow rate. The neutral depletion effect that has been observed near the exit plane for a medium power Hall device [35-36] provides supporting evidence. We can understand why this is important via a simple calculation of the collision probability for backstreaming neutrals returning from the far end of the chamber. We write the first order rate equation neutral density in the ion beam as

$$-\frac{d\rho}{dt} = I_b \sigma \rho, \quad (15)$$

where ρ is density of unreacted xenon neutrals, I_b is ion beam intensity and σ is the $\text{Xe}^+ - \text{Xe}$ charge exchange cross section, and rewrite after integration as

$$\rho(t) = \rho_0 e^{-I_b \sigma t}. \quad (16)$$

For a hypothetical 15 Ampere ion beam uniformly distributed over 300 cm^2 area, we obtain after 3 milliseconds $e^{-\left(\frac{15}{300}\right)\left(\frac{5.5\times 10^{-15}}{1.6\times 10^{-19}}\right)(0.003)} = \frac{\rho(t)}{\rho_0} = 0.0058$. For a thermalized xenon neutral approaching the thruster from 25 cm away with axial velocity of 75 m/s, the transit time is about 3 milliseconds and the probability of reaching the thruster unreacted is extremely small. However, for a 1 Ampere ion beam neutrals are likely to arrive without experiencing charge exchange, and if we double the velocity this outcome is even more probable. This is the crudest of models but it shows the qualitative importance of ion beam intensity and velocity of the backstreaming neutrals. In addition, since the pressure measurement apparatus cannot be located precisely at the entrance to the thruster discharge channel it will sample neutrals that experience lower ion beam intensity.

Table I. Illustration of relationships between directed xenon velocity, density, and ingestion rate.

n_{re} (random external density)	T_{re} (external temp)	n_g (IG on sphere)	v_d (directed velocity, m/s)	n_{dg} (direct-random in IG)	n_{de} (ext directed)	n_{te} (total external)	Ingestion Ratio
5.0E+10	155	7.5E+10	300	3.84E+10	7.7E+09	5.77E+10	2.1
5.0E+10	155	7.5E+10	500	3.84E+10	4.6E+09	5.46E+10	2.1
5.0E+10	155	7.5E+10	1000	3.84E+10	2.3E+09	5.23E+10	2.1
5.0E+10	155	1.0E+11	300	6.34E+10	1.27E+10	6.27E+10	2.7
5.0E+10	155	1.0E+11	1000	6.34E+10	3.8E+09	5.38E+10	2.7
5.0E+10	155	1.5E+11	1000	1.13E+11	6.8E+09	5.68E+10	4.1
5.0E+10	155	2.0E+11	1000	1.63E+11	9.8E+09	5.98E+10	5.5
5.0E+10	155	3.0E+11	1000	2.63E+11	1.58E+10	6.58E+10	8.2

Neutrals with elevated velocity of approach due to incompletely thermalized directional flow, and those that approach from oblique angles, have an advantage with respect to achieving thruster ingestion if the ion beam presents an effective shield. In any case, the situation is too complex to be treated accurately by a 1D model, which has been the standard approach.

III. Results

Table II documents xenon pressure measurement results at constant 28 sccm xenon flow rate, for both cold and hot flow cases. They are corrected for sensitivity and baseline reading at zero flow rate. The cold flow pressure data are plotted in Fig. 4 as a function of the number of custom rings operating. In each case there were three PHPK (TM-1200i) pumps operating together with the custom rings, however the “zero” case is different in that four of the TM-1200i were on and it is a hot flow case. A single custom ring is enough to dominate the overall pumping speed, as evidenced by the precipitous pressure drop in going from 0 to 1 custom ring. The sphere, wall and standard internal measurements coincided very well for the hot flow “zero” case, which has the pumping localized to the downstream end of the chamber, with little pumping speed. Therefore, the background pressure is relatively high and relatively uniform in the facility. With 1-4 custom cryorings operating the sphere and internal readings coincide closely. There is a small divergence between these for the hot flow “zero” case, which we will see is accentuated for all hot flow cases with custom rings operating. Note also that the wall reading diverges from sphere and internal readings with any number of cryorings operating and typically is about half their reading. The two downstream gauges were aligned with each other at “zero”, reading substantially higher than the upstream gauges. However, they strongly diverged when custom rings were operating; the thruster-view gauge dropped dramatically and aligned with the wall gauge while the dome-view reading declined much more slowly. The latter gauge was significantly influenced by operation of its heater, especially at low pressure, limiting any conclusions based on its data. While it suggests there is considerable flux enhancement for any gauge staring at the end wall of the chamber – presumably due to a virtual source of neutrals being generated at the beam stop - we will not attempt to quantify the enhancement. The relatively slow decline of this gauge reading with number of operating custom rings may make sense in terms of the constancy of the virtual neutral source it is viewing, together with the reduced background of neutrals that are being pumped away.

Fig. 5 captures pressure data for the five gauges as a function of cold flow rate through the right-hand thruster, with one custom ring operating. Internal and spherical results coincided very well. Wall and thruster viewing gauges also coincided but not as closely, and at considerably lower pressure than the other pair. The dome viewing result was substantially higher than all the others, even after dividing the reading by a factor of two. Linearity of the pressure reading with flow rate was very good in all cases except thruster viewing, which – like the dome viewing gauge - was influenced at low pressure by operation of its heater. Data shown at 28 sccm flow rate are the same as Fig. 4 data with Ring 1 operating.

Table II. Hot and cold flow results for selected pumping configurations at 28 sccm xenon flow rate. LN2 cooling for all pump chevrons, radiation shields etc was always in effect, regardless of sail temperature, except for the PHPK-only hot flow case. All pressures are given in microtorr.

Pumping Configuration	Pressure (Internal)	Pressure (Sphere)	Pressure (Wall)	Pressure (Thruster view)	Pressure (Dome view)
4 PHPKs (hot flow); no LN2 cooling of custom shrouds	5.81	6.02	5.61	10.7	9.68
Ring 1, 3 PHPKs (cold flow)	1.61	1.63	0.94	0.85	5.45
Rings 1&2, 3 PHPKs (hot flow)	0.90	1.18	0.56	0.35	3.84
Rings 1&2, 3 PHPKs (cold flow)	0.85	0.89	0.40	0.43	2.94
Rings 1-3, 3 PHPKs (hot flow)	0.69	0.99			
Rings 1-3, 3 PHPKs (cold flow)	0.63	0.69	0.31	0.27	1.70
Rings 1-4, 3 PHPKs (hot flow)	0.64	0.93			
Rings 1-4, 3 PHPKs (cold flow)	0.59	0.65	0.30	0.16	1.3

Fig. 6 includes hot flow data with both thrusters on, at the nominal total flow rate with rings 1 and 2 operating. Pressure readings are down across the board, relative to ring 1 only, as expected. As usual, the cold flow went through the right-hand thruster. There is a pronounced deviation between the hot flow and corresponding cold flow fit line for the spherical data, indicating the observed return flux is enhanced when the thrusters are operating

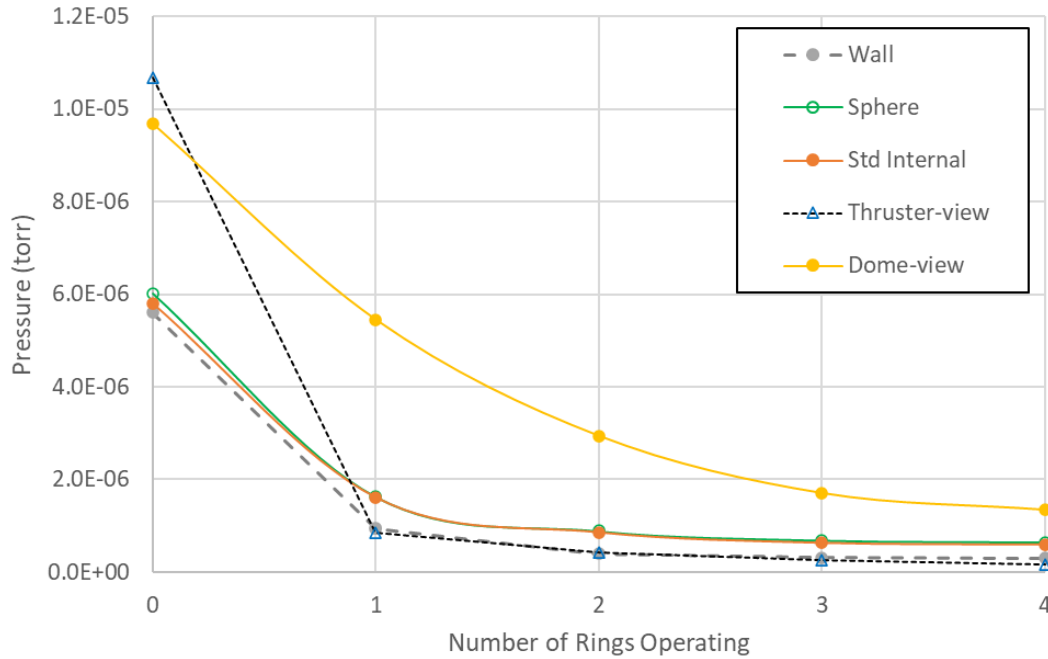


Fig. 4 Pressure measurements as a function of the number of operating custom cryorings. The total flow rate was 28 sccm. The “zero” case was hot flow and all others were cold flow. For 1-4 custom rings three TM-1200i pumps were operating (four of these for the zero case).

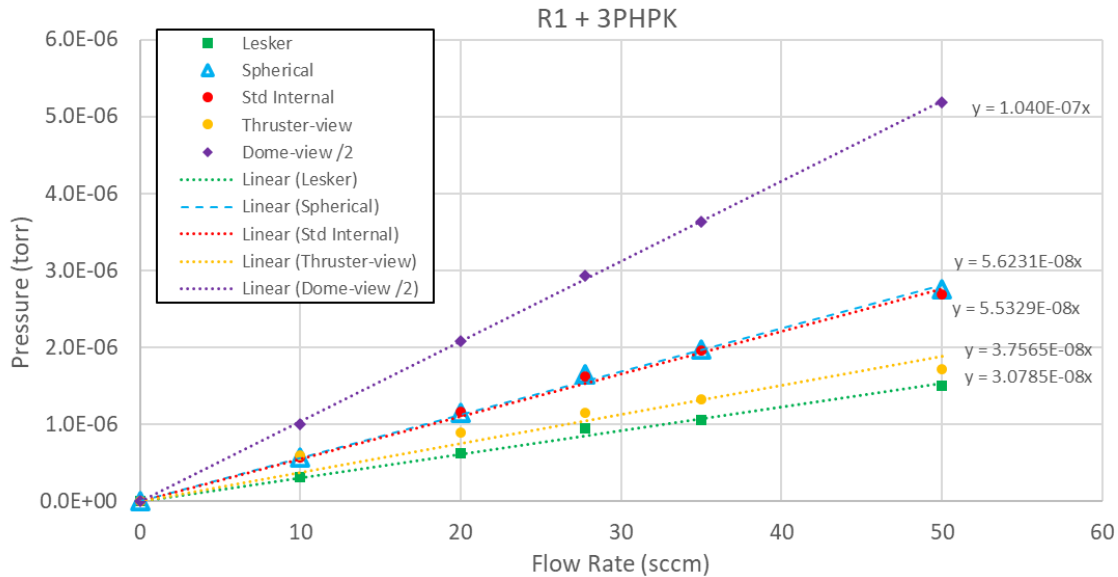


Fig. 5 Cold flow ion gauge data obtained with just Ring 1 (situated behind the thrusters) and three PHPK pumps operating. All flow went through the right-hand thruster. No hot flow data were obtained for this case.

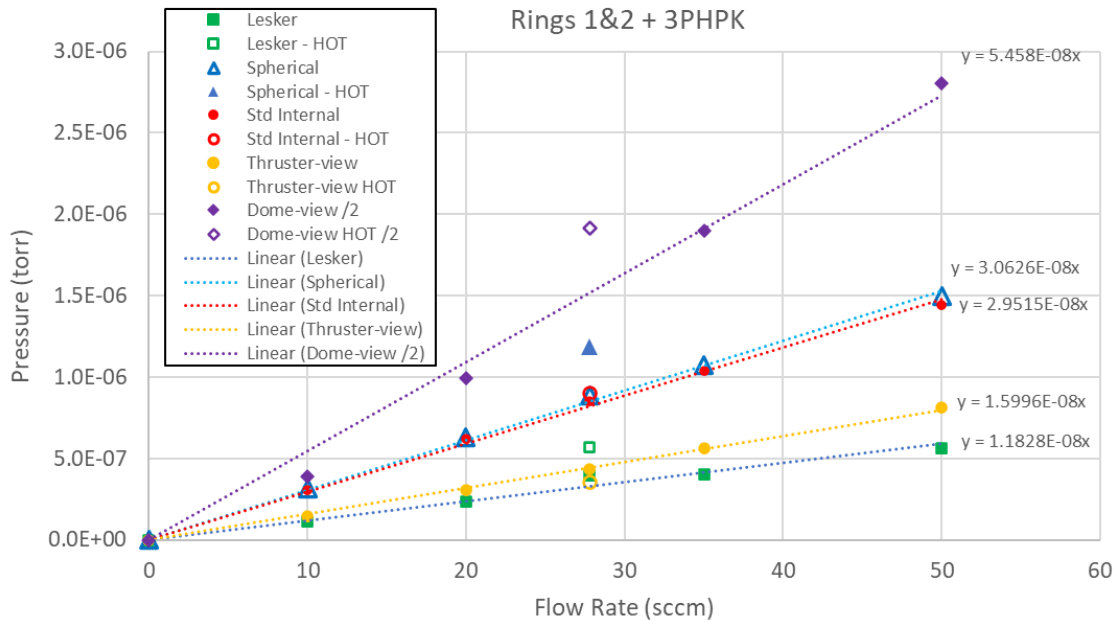


Fig. 6 Ion gauge data obtained with Rings 1 and 2 operational. Hot flow results with both thrusters on are included (28 sccm total flow), clearly deviating from the corresponding cold flow fits in several cases.

instead of just flowing cold gas. This deviation is also reflected by the dome-view gauge. The standard internal gauge, on the other hand, is only slightly elevated with respect to the cold flow fit. We see elevation of pressure at the wall also, whereas pressure recorded by the thruster viewing gauge is depressed.

Results in Fig. 7 were obtained with rings 1-3 operating. The left panel displays data in the same way as previously done, whereby cold flow goes through the right-hand thruster and hot flow is divided evenly between the two thrusters. Here we again see substantial hot flow pressure elevation for the sphere and relatively little for the standard internal gauge (hot flow results are only available for sphere and standard internal gauges). The wall gauge indicates moderate elevated pressure at 28 sccm cold flow, with flow divided equally between thrusters as usual. The right panel displays cold flow results with all flow going through the left-hand thruster. Because the flow controller for the left-hand thruster was less accurate its nominal reading was scaled to coincide with the right-hand flow settings. Only the three most reliable gauges are included in the plot. The wall gauge indicates substantial pressure increase when flow goes through the left-hand vs right-hand thruster. There is little or no change for sphere and internal, but the wall-mounted gauge is about 50% higher. The wall gauge has a better view factor to the left-hand thruster, which presumably explains (at least in part) why it sees neutral flow from this thruster more readily. Pressure elevation of this gauge during hot flow conditions can therefore be understood, to some degree, by the fact that flow through both thrusters is involved.

With all four custom rings operating, pressure readings of the two downstream gauges drop the most (see Fig. 8). Pressures for the other three gauges are only slightly lower than the three-ring case. These results are no doubt influenced by the proximity of ring 4 and downstream gauges. Pressure elevation for the sphere during hot flow stands out, as before.

Pressure profiles recorded during a portion of the day on which Fig. 8 data were collected, are plotted in Fig. 9. Sphere and standard internal profiles are shown for both hot and cold xenon flow conditions. The ratio of cold to hot flow pressure is obviously lower for the sphere. These data provided the scaling factors to obtain corrected LH thruster flow rate plotted in Fig. 7. The corresponding flow rate profile (uncorrected) for these results is given in Fig. 10.

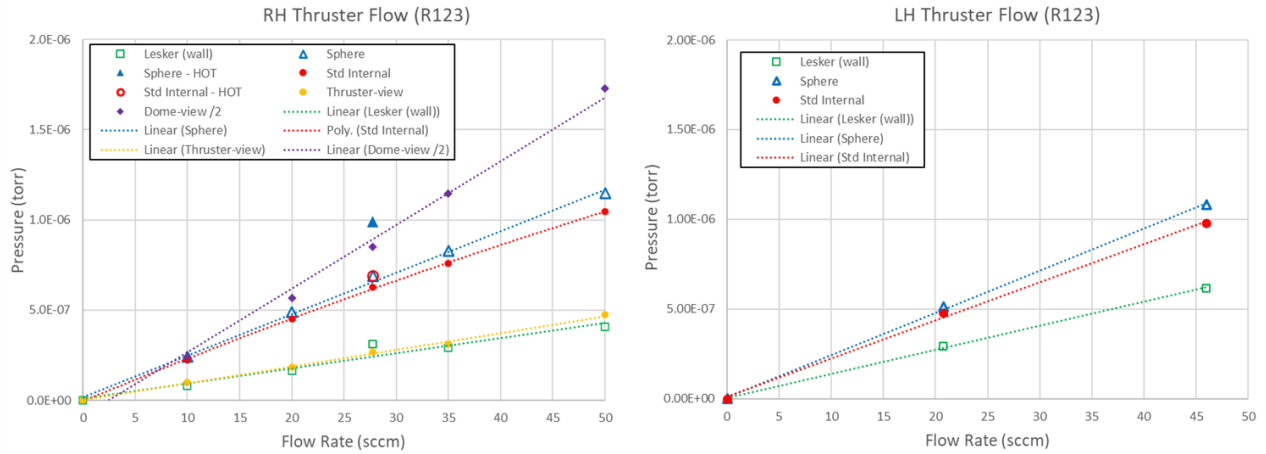


Fig. 7 Pressure data obtained with Rings 1-3 operating and cold flow through the right-hand thruster anode. Two additional data points for 28 sccm hot flow divided evenly between thrusters is also shown. The right panel data were obtained with cold flow through the left-hand thruster anode. Hot flow data points were only obtained for sphere and standard internal gauges.

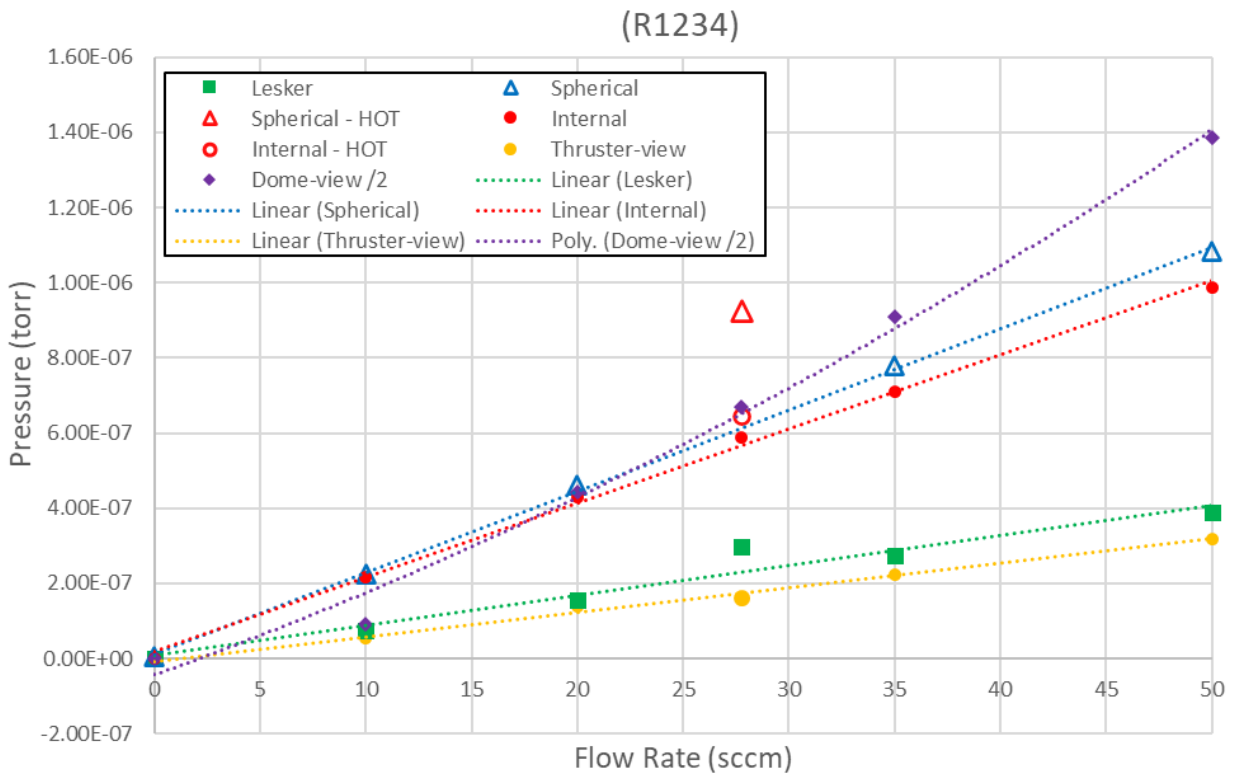


Fig. 8 Ion gauge data obtained with all four custom cryorings operating. Hot flow pressure measured at the spherical chamber is significantly elevated, in keeping with the established pattern. Hot flow data points were only obtained for sphere and standard internal gauges.

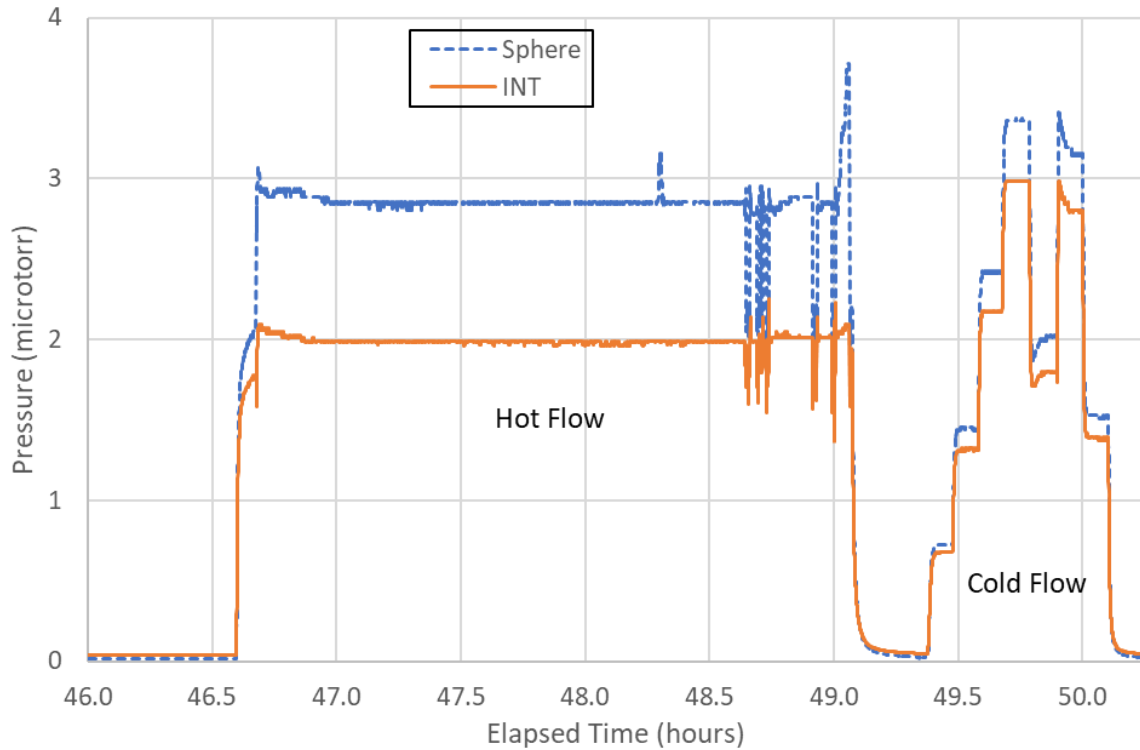


Fig. 9 Sphere and standard internal pressure gauge data with three custom rings operating. A sequence of cold flow settings was used to generate pressure vs flow rate plots. The hot to cold flow pressure ratio is higher for the sphere.

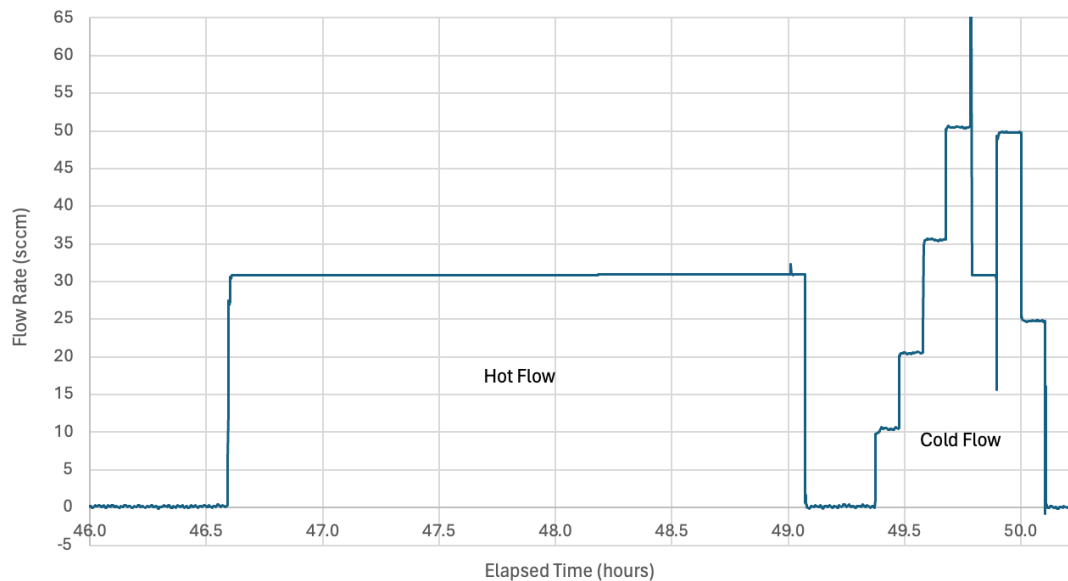


Fig. 10 Xenon flow rate profile for Figure 9 data (uncorrected).

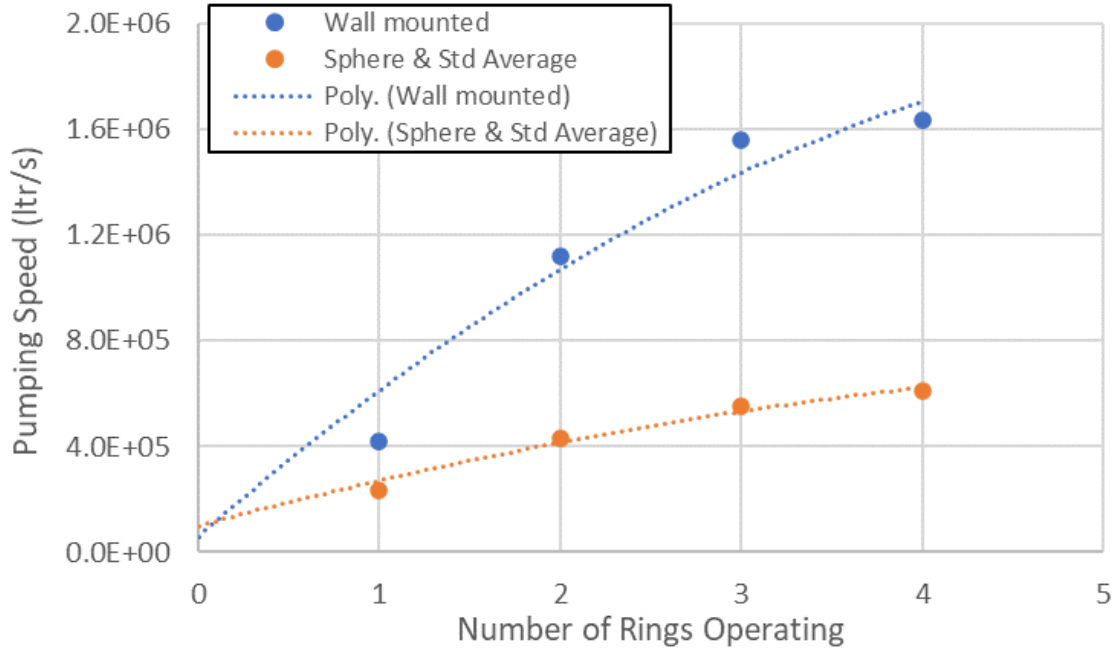


Fig. 11 Xenon pumping speed dependence on number of operating custom cryorings, for internal measurements near the thruster pair and at the wall, during 50 sccm cold flow through the right hand thruster.

Pumping speed determined from the ionization gauges located near the thrusters and at the wall are plotted vs number of operating custom rings in Fig. 11. The apparent pumping speed according to the internal gauges is presumably lower because they see directed flow, increasing the pressure reading due to the dynamic flow contribution that is on top of the static component. The wall gauge sees the static component, with virtually no dynamic component, and is located at about a meter or less distance away from a cryopumping surface if either ring 1 or ring 2 is operative – keeping the static component in check and producing high calculated pumping speed. If we use the thruster-view gauge to compute pumping speed the result is even higher, 2.0×10^6 ltr/s with rings 1-4 operating and 50 sccm cold flow. The pressure here may be reduced by a wake effect in the directed flow. [22] On the other hand, for the sphere and the standard hot flow condition the pumping speed is just 3.9×10^5 ltr/s. As another comparison point, during the operation of a more powerful Hall thruster the pumping speed derived from standard internal gauge readings clustered around 1.0×10^6 ltr/s.

IV. Discussion

Since vacuum pumps are a sink for propellant, a low-pressure region is created around them with associated density gradient, and neighboring gas acquires a mean velocity in the pump direction. The gradient and local gas velocity increases proportionally with sticking coefficient and pump to chamber cross sectional area ratio, for a 1D model. [20] For the unlikely conditions where sticking coefficient and area ratio each approach unity, the mean flow velocity is well below the velocities assumed in Table I. EP3 is unusual in having most of the side wall area covered by cryopumps, but since they are distributed so uniformly along the wall the mean axial flow velocity due to pumping may be limited. Also, the 1D model does not anticipate the difference between cold and hot flow observed in the present study. It assumes all neutrals are perfectly thermalized regardless of flow condition.

The flux ratio for a thermalized gas with bulk velocity to gas without has been computed by Yim [22]. If the ratio of bulk mean flow velocity to mean thermal velocity of static gas is 0.2, the flux ratio is nearly 1.5. If the ratio is 0.4 the flux ratio exceeds 2. Since the sphere and standard internal gauge readings are 2-3 times the wall

pressure under cold flow conditions, the corresponding mean bulk flow velocity would be roughly half the mean thermal velocity. However, the wall gauge does not have the same view of virtual gas sources as the gauges underneath the thruster pair; it is somewhat protected by cryoring 2 and the pressure ratio could be artificially enhanced as a result. The spherical accommodation chamber is receptive to all incoming particle flux, whether the gas is fully thermalized, has a modest bulk velocity offset imposed on a Maxwellian distribution or is hyperthermal and directional. During hot flow we expect all these situations exist concurrently and each contributes to the measured flux. The standard internal gauge sees all these contributions but fails to fully register hyperthermal particles, and therefore gives a reading that is substantially higher than wall and thruster-view gauges but lower than the spherical gauge during hot fire.

While the $\sim 5\times$ hot flow sphere relative to thruster-view pressure (or even $3\times$ hot flow sphere to cold flow wall) observed with all rings running would be adequate to explain the typical ingestion deficit for Hall thrusters, relative to estimates based on a fully thermalized assumption, there are cases where the claimed discrepancy is $10\times$ or even greater. The neutral depletion that was observed near the exit plane of the SPT-140 thruster [35-36] would perform a similar role as a cryopump, drawing background neutrals into the plume and generating bulk velocity. The neutral depletion exists at the exit plane and in addition to persisting until about 50-cm downstream may extend into the discharge chamber, elevating ingestion rate. Due to the resulting bulk radial velocity acquired by the background gas and the surface area of the cylinder surrounding the depleted region – considerably larger than the area of the discharge channel – this mechanism may be an important contributor to the ingestion rate. In addition, chamber geometry will certainly influence results. Less distance between thruster and end wall, as well as reduced chamber diameter, would be consistent with higher ingestion. Moving the entrance aperture closer to the thrust axis may reduce the pressure reading due to reactions of the ion beam with background neutrals. Beam stop geometry [30,37] and thruster magnetic field settings are potential factors as well.

While there is some information available regarding how xenon ions come away from surfaces as neutrals, we were unable to find any measurement or simulation results for Xe^+ collisions with carbon – a typical situation in electric propulsion chambers. Since xenon atoms are heavy and carbon is light, a not insignificant fraction of energetic ions will likely reflect as hyperthermal neutrals. This is especially true for oblique angles of incidence, but reflections from the carbon beam stop back toward the thruster are expected to occur. For example, simulated reflections for 300 eV Xe^+ incident on aluminum and titanium targets with angle of incidence less than 30 degrees are peaked at perpendicular and have nearly the same angular distribution as perpendicular incidence. [24] The average energy after reflection is less than 5% of the original but is very high for larger angles of incidence; at 60 degrees it is 53% for Al and 37% for Ti. Simulation of Xe^+ impacting nickel surfaces at normal incidence produced average reflection energy of about 4 eV, with high reflection probability at low energy that tailed off to zero by 1000 eV. [27] When the ions were sufficiently energetic they implanted, and were later released as the surface eroded further. Since sputtered atoms typically have average energy of several eV, the released xenon is also expected to be hyperthermal, but with broadened angular distribution. Accommodation of hyperthermal xenon improves as the surface temperature is lowered, [19] so that the temperature of a small internal chamber attached to an internal ion gauge could affect the pressure measurement.

The use of a 1D conductance model for pumping speed estimates is flawed for electric thruster hot flow conditions and will typically underestimate the pumping speed. [31] It does not properly allow for directional flow, whether induced by pumping or hyperthermal reflection of energetic ions, nor distributed gas sources and beaming effects. 1D flux models can do considerably better, and Direct Simulation Monte Carlo (DSMC) is a further improvement, especially if the right physics are included. Accurate accommodation coefficients are not generally available, and multiple factors influence results.

Ion gauge placement at the chamber wall, axially located at the exit plane has been recommended for electric thruster testing and reporting. [25] This is the location of the wall-mounted gauge in the present study. Clearly this fails to capture the potential magnitude of thruster ingestion rate. Much has been written about the failure of ingestion rate calculations for background propellant crossing the exit plane and re-entering the thruster, based on a wall-mounted gauge coincident with the exit plane. These calculations assumed fully thermalized gas with isotropic velocity, and invariably could not produce high enough ingestion to explain the observed data. Various hypotheses have been proposed to explain the discrepancy, with insufficient supporting evidence. The

magnitude of the apparent elevation of ingestion rate observed in the present study is of similar size as the typical discrepancy, which is manifested by the need to decrease anode flow rate as background pressure is increased, to maintain constant discharge current. [1,3,7]

Rising thrust level with increasing background pressure has been observed almost universally for Hall devices, together with the need to reduce anode flow rate if operating point is to be maintained, as chamber pressure rises. Even if the flow rate is carefully reduced to keep the beam current steady, thrust is generally observed to rise quickly at low pressure and level off at high pressure. Again, various hypotheses have been proposed to explain these observations, including at least one that mimics the typically observed thrust augmentation vs pressure profile. [38]

V. Conclusion

This is the first study using an internal chamber with high effectiveness for accommodating the background gas to its wall temperature. As part of the study a simple model was developed to illustrate the effect of directional flow on ingestion rate and pressure measurements. The results advance the understanding of facility effects and can lead to better ground test methodology and improved predictions of in-space performance and propellant flow rate inputs for ion thrusters. High pumping speed and low facility interactions are critical design goals for electric propulsion test facilities, to better simulate the space environment and properly evaluate high power devices. The difficulty in achieving high fidelity testing increases with power level and use of thruster clusters. The facility utilized here has the highest pumping speed of any dedicated electric thruster test chamber. Using multiple ion gauges at various points inside the test facility, and a spherical internal chamber for improved gas accommodation, comparison between hot and cold flow data demonstrates that flow dynamics inside the test facility are more complex than has generally been realized. It shows that “standard” ways of measuring pressure are inadequate for determining the propellant ingestion rate of operating electric thrusters because they do not accurately measure flux. This is because they do not ensure the gas is fully thermalized at the measurement point. Side by side measurements revealed a distinct difference between hot and cold flow results when the gas is properly accommodated, and relatively little difference when taking a more standard approach. The hot flow ingestion rate was found to be substantially higher than the cold flow rate, which goes a long way toward explaining past discrepancies between measured and calculated rates based on a fully thermalized assumption with no directed flow. The assumption made repeatedly in the past - that energetic ions and neutrals are completely accommodated to the local surface temperature after a single collision with that surface - is false. The new result is the first observation of propellant back flux elevation at the thruster exit plane when the device is turned on, providing insight into physics of the facility and its interaction with the Hall thruster.

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