Alternative propellant study (krypton vs. xenon) of the µ10 ECR Gridded Ion Thruster at its Hayabusa2 and DESTINY+ Missions

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A first krypton vs. xenon experimental comparison on the µ10 Electron Cyclotron Resonance (ECR) Gridded Ion Thruster is presented, carried out on at its respective configurations for the DESTINY+ and Hayabusa2 missions. The ion sources and their ECR neutralizer have been investigated separately. The analysis of the data reveals that for krypton, by adjusting the operating point, the ion sources deliver similar current in the same propellant consumption range. Krypton can reach equivalent thrust levels to xenon for both configurations, nevertheless, a deterioration of the overall performance of about the 30% occurs. The former loss is mainly due to the increased propellant demand of the neutralizer, which more than doubles for krypton vs. xenon, for comparable current levels.

Key words: Krypton, Xenon, ECR Ion thruster, Hayabusa2, DESTINY+.

Nomenclature

I_{sc}	:	screen current, mA
I_{ac}	:	acceleration current, mA
I_b	:	beam current, mA
$\dot{m}_s$	:	ion source mass flow rate, mg/s
$\dot{m}_{s,i}$	:	ionized ion source mass flow rate, mg/s
V_n	:	neutralizer anode voltage, V
I_n	:	neutralizer current, mA
$\dot{m}_n$	:	neutralizer mass flow rate, mg/s
η_d	:	ion discharge loss, eV/ion
P_{MW}	:	ion source forward microwave power, W
η_u	:	mass (/propellant) utilization efficiency

Abbreviations and acronyms

Kr	:	krypton
Xe	:	xenon
GIE	:	Gridded Ion Engine xenon
ECR	:	Electron Cyclotron Resonance

1. Introduction

The µ10 Gridded Ion Thruster technology has more than two decades of flight operation heritage as main propulsion system, on board on the Japanese Hayabusa missions. It has been the pioneer electric propulsion system applying ECR technology in space.[1–4)] New improvements, focused on enhancing performance and lifetime, are being carried out for the DESTINY+ mission, expected to launch in 2024.[5,6)]

Thanks to its low ionization energy, large atomic mass, and inertness, xenon is the standard propellant used in electric propulsion, despite its limited availability and cost. In recent times, the interest in alternative propellants, to be used alone or in xenon mixtures, is rising noticeably. Table 1 includes a comparison between xenon and the most common alternative propellants, as iodine —similar mass, solid and less ionization energy, but corrosive—, krypton, and argon —both inert, but less massive and higher ionization energy, especially the latest— are being actively studied. Krypton, about the 10% of xenon price, stands out as a promising prospect for easier handling than iodine.[10–14)]

Table 1. Propellant properties comparison.

	Xenon	Krypton	Argon	Iodine
Atomic mass, uma	131.293	83.798	39.948	126.904
1st Ionization energy, eV	12.13	14	15.76	10.45
Other comments	Inert	Inert	Inert	Solid, corrosive

This report presents the first experimental comparison of the use of krypton vs. xenon on three different devices: the DESTINY+ and Hayabusa2 µ10 ion sources, and the ECR neutralizer they use.[7–9)] Thruster performance is derived from electrical measurements.

The following content is structured as follows. Section II describes the experimental setup. Section III shows the measurements and the overall performance metrics. Finally, Section IV summarizes the conclusions and next steps.

2. Experimental setup

The µ10 ion sources of Hayabusa2 and DESTINY+ are composed of an ECR ionization chamber and a set of screen, acceleration, and deceleration grids as shown in Fig. 1. The discharge chamber is electrically connected to the screen grid. In the present experiments, the sources are operated without external neutralizer, by grounding the deceleration grid. The operating conditions are detailed in Table 2. The Hayabusa2 and DESTINY+ ion sources are essentially identical except for the arrangement of the downstream magnets, the grid sizing, and the location of the gas injectors.[5)] The electric current to the screen grid I_{sc} and acceleration grid I_{ac} are measured with a resolution of 1 and 0.1 mA, correspondingly —the ion beam current I_{b} is defined as $I_{\mathrm{sc}} - I_{\mathrm{ac}}$.

The neutralizer consists of an ECR ionization chamber, with a single gas injector at the rear, as shown in Fig. 2. It has been tested separately from the ion sources, using an auxiliary anode. The anode voltage V_n was kept under 50 V. Table 3 summarizes its main characteristics and operating conditions. For each discharge current I_n set, the V_n is measured with a resolution of 0.01 V.

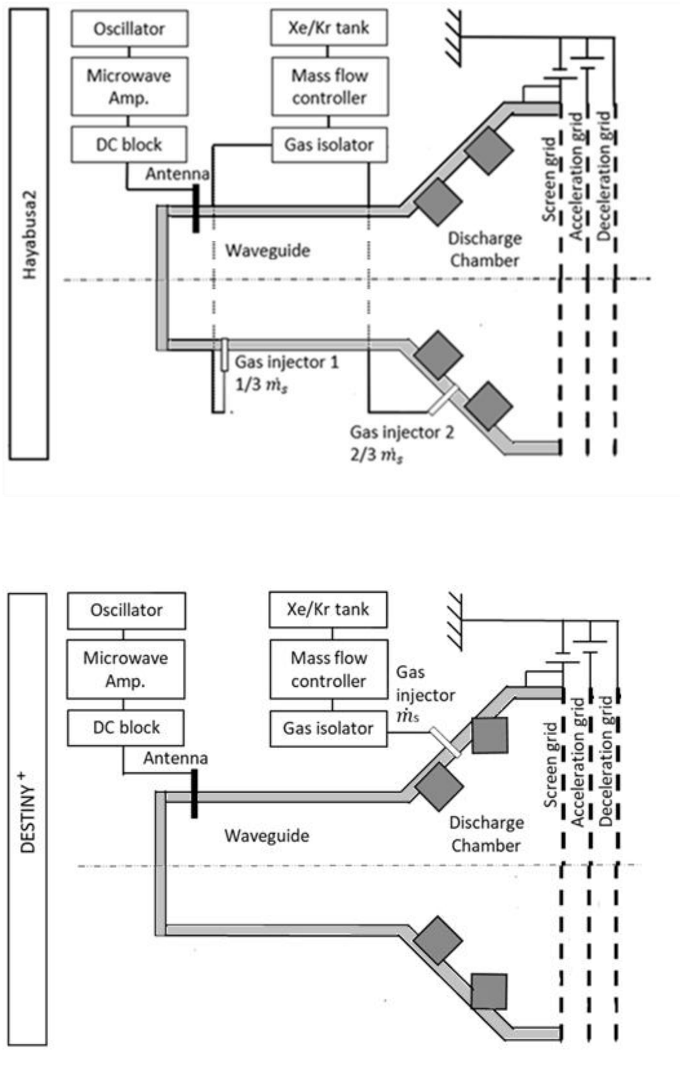


Fig. 1. Schematic of the ion beam extraction experiment of the Hayabusa2 (top) and DESTINY+ (bottom) µ10 sources using krypton and xenon.

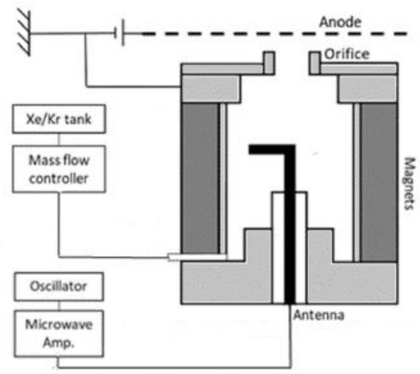


Fig. 2. Schematic of the diode-mode test of the ECR neutralizer cathode, which is used for Hayabusa2 and DESTINY^{+}.

Table 2. Ion beam extraction experiment characteristics of the μ10 sources using krypton and xenon.

	Hayabusa2	DESTINY^{+}
Magnet configuration	Inner: 45º Outer: 45º	Inner: 45º Outer: 90º
Propellant injection points	Waveguide Discharge chamber	Discharge chamber
SC grid thickness, mm	0.8	0.5
AC grid thickness, mm	1.0	1.0
AC grid orifice diameter, mm	1.5	1.2 – 1.4
SC-AC grid distance, mm	0.5	0.6
Open area diameter, mm	105.0	
Wave frequency, GHz	4.25	
Forward microwave power, W	34	
Screen Voltage, kV	1.52	1.525
Acceleration Voltage, V	−370	
Propellant flow rate[1], sccm	Xe: 1.0 – 3.4 Kr: 1.0 – 5.0	Xe: 1.0 – 3.1 Kr: 1.0 – 4.1
Background pressure during operation, Pa	$<5.00 \times 10^{-3}$	

Table 3. Characteristics of the diode-mode test of the ECR neutralizer cathode.

Wave frequency, [GHz]	4.25
Forward microwave power, [W]	8
Anode voltage, [V]	<50
Propellant flow rate[1], [sccm]	Xe: 0.3 – 0.8 Kr: 0.3 – 3.0
Background pressure during operation, [Pa]	$<4.00 \times 10^{-3}$

3. Results

Fig. 3 collects the measured currents I_{sc} and I_{ac} for the two tested ions sources as a function of the mass flow rate $\dot{m}_s$. In the Hayabusa2 source, the screen grid current shows a single maximum for both propellants. This maximum current is larger for krypton (216 mA) than for xenon (171 mA), but it is reached at slightly higher $\dot{m}_s$, 0.24 (3.8) vs. 0.22 mg/s (2.2 sccm) respectively. Beyond this mentioned peak, I_{sc} decreases from the "high current mode" (HCM) into the inefficient "low current mode" (LCM), described in [15–17], with an associated increase of the reflected microwave power. For xenon this transition seems more abrupt. On the other hand, I_{ac} presents a minimum at 0.18 (1.8) – 0.19.mg/s (1.9 sccm) and 0.16 (2.5) – 0.20 mg/s (3.3 sccm) for xenon and krypton correspondingly.

In the DESTINY+ source, results are comparable in magnitude and trend to the Hayabusa2 case, except for the following. I_{sc} grows monotonically for xenon with $\dot{m}_s$, reaching 200 mA at 0.28 mg/s (2.9 sccm), while the curve for krypton has a local maximum at 0.20 mg/s (3.2 sccm) and a minimum around 0.22 mg/s (3.5 sccm), prior to reach the highest current in the measurement range, 200 mA at 0.24 mg/s (3.8 sccm). I_{ac} is generally larger than in the Hayabusa2 source and decreases monotonically with $\dot{m}_s$. The transition between the HCM and the LCM is more sudden for the DESTINY+ than for the Hayabusa2 sources. In the case of xenon, these transitions may occur at any $\dot{m}_s$ > 0.23 mg/s (2.3 sccm). By contrast, for krypton, the high current mode is stable up to surpass its I_{sc} absolute maximum at 0.24 mg/s (3.8 sccm), after which just the LCM exists.

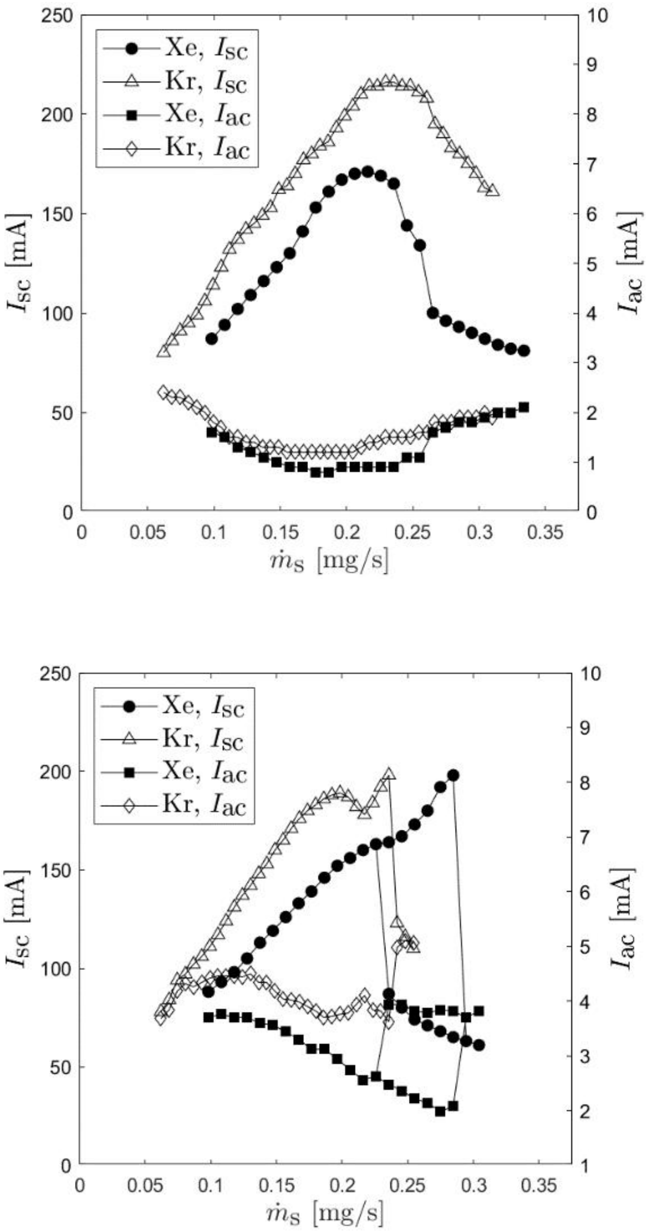


Fig. 3. Krypton vs. xenon comparison of the screen current I_{sc} and acceleration current I_{ac} of the Hayabusa2 (top) and DESTINY⁺ (bottom) μ10 ion source configurations, as a function of the mass flow rate $\dot{m}_s$.

For the two ion sources, at identical particle injection rates during the HCM, xenon provides higher I_{sc} than krypton —which involves larger $\dot{m}_s$. for Kr. This is expected due to the ionization energy gap. However, the transition to the LCM happens —or may happen, in the case of DESTINY⁺,—at a lower I_{sc} for xenon than for krypton. This allows krypton to reach the highest I_{sc}

Fig. 4 depicts the discharge loss η_d vs. the mass utilization efficiency η_u, formulated in [18]. This graph represents the source production performance at certain ion current, given the $\dot{m}_s$ and the microwave power P_{MW}. η_d is minimal at an intermediate $\dot{m}_s$ where $I_b = I_{sc} - I_{ac}$ is maximum, for both prototypes and propellants. The lowest η_d occurs for the Hayabusa2 source and krypton, with only 150 eV/ion at 0.24 mg/s (3.8 sccm). The mass utilization efficiency η_u increases when $\dot{m}_s$ is reduced, and it saturates below the $\dot{m}_s$ at which η_d is minimum. The authors note those values $\eta_u > 1$ are an artifact of a computation which neglects multiply charged ions.

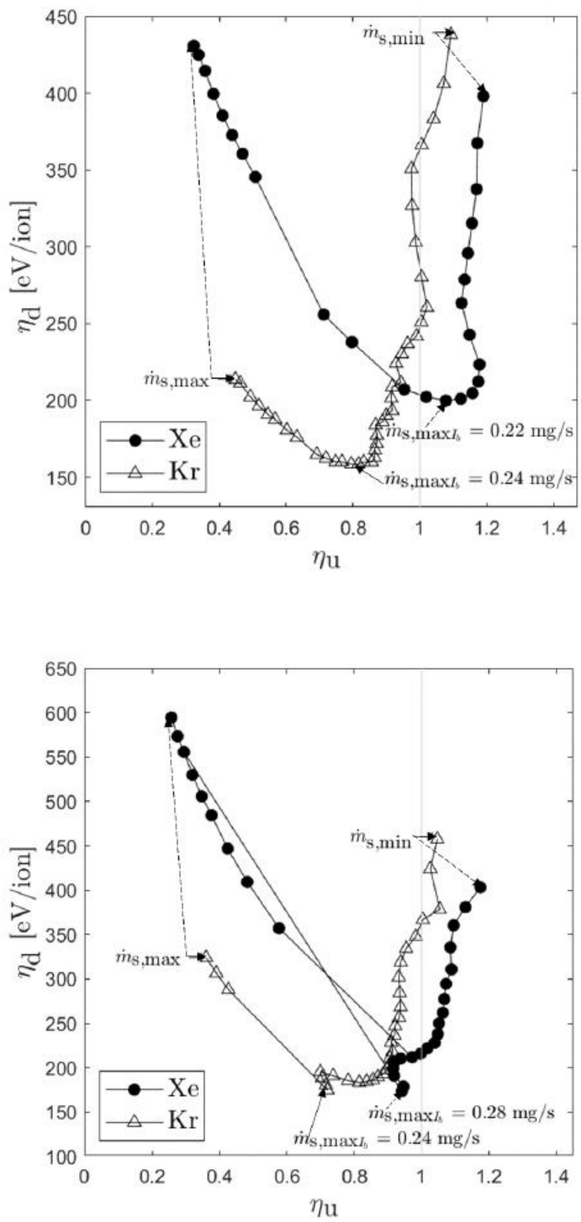
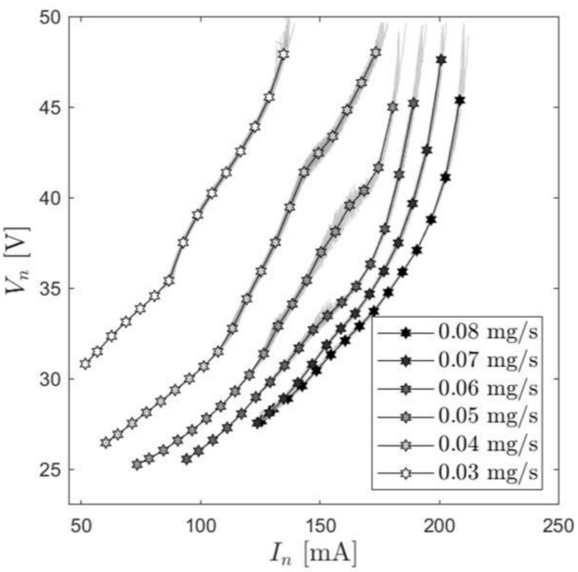


Fig. 4. Krypton vs. xenon comparison of the estimates of the ion source discharge loss $\eta_d = P_{MW}/I_b$ vs. mass utilization efficiency $\eta_u = \dot{m}_{s,i}/\dot{m}_s$ (defined for singly

charged ions) of the Hayabusa2 (top) and DESTINY$^+$ (bottom) μ10 ion source configurations.[18)]



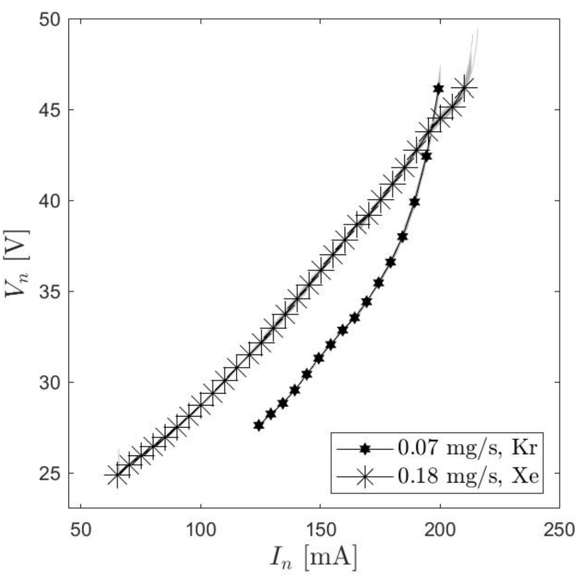


Fig. 5. I_n-V_n curves of the neutralizer cathode operating in diode mode. Top: xenon curves as a function of the mass flow rate $\dot{m}_n$. Bottom: krypton vs. xenon curves at a specific $\dot{m}_n$. The shaded area represents the hysteresis detected during the experiment when increasing/decreasing I_n.

The neutralizer cathode characterizing I_n-V_n curves are shown in Fig. 5. for the two propellants, at different $\dot{m}_n$—unstable operation at, approximately, V_n< 25 V for Xe and I_n< 60 mA for krypton. For a given $\dot{m}_n$, the V_n increases smoothly with the I_n drawn. In the range explored, increasing $\dot{m}_n$ results in a lower V_n for a set I_n. Overall, a higher amount of krypton is required to operate the cathode at the same I_n-V_n point, e.g., at 200 mA-45V, 0.17 mg/s (2.8 sccm) for krypton vs. 0.07 mg/s (0.7 sccm) for xenon; which means the neutralizer is less efficient with krypton. Additionally, small but measurable hysteresis was observed at some values of $\dot{m}_n$ while increasing/decreasing I_n, shown as shaded area.

Table 3. Krypton vs. xenon comparison of the Hayabusa2 and DESTINY$^+$ performances at the operating point where the beam current I_b becomes maximum in each case, in the explored range. Performance figures are defined as in [18)].

	Hayabusa2		DESTINY$^+$	
	Kr	Xe	Kr	Xe
Ion source flow rate, mg/s (sccm)	0.24 (3.8)	0.22 (2.2)	0.24 (3.8)	0.28 (2.9)
Cathode flow rate, mg/s (sccm)	0.18 (2.9)	0.06 (0.6)	0.17 (2.6)	0.08 (0.8)
Beam current, mA	215	170	194	196
Thrust, mN	10.2	10.1	9.2	11.7
Specific impulse, s	2502	3774	2402	3290
Total power, W	489	408	458	455
Thruster (or total) efficiency, %	26	46	24	41

(Flight model) Thrust correction factor = 0.92 [1].

Finally, the results from the separated experiments of the ion sources and the neutralizer have been considered together to estimate the overall thruster performance. Table 3 summarizes the main propulsive figures of merit as defined in [18)], for the operating point that maximizes I_b in each case. The efficiency and specific impulse of both systems (Hayabusa2 and DESTINY$^+$) are degraded for krypton, mainly because the required $\dot{m}_n$ becomes comparable to $\dot{m}_s$. This value is not compensated by the lower η_d shown by krypton discussed above for Hayabusa2. The thrust estimates for Hayabusa2 are similar for krypton and xenon, around 10 mN. For DESTINY$^+$, a slightly lower thrust is expected for krypton (9.2 mN against 11.7 mN for xenon), a result driven mainly by the atomic mass decrease.

4. Conclusions

A first krypton vs. xenon experimental comparison on the DESTINY+ and Hayabusa2 μ10 ion sources, and their ECR neutralizer, is presented. When operating on krypton, by adjusting the working point, the ion sources deliver similar current and in the same propellant consumption range. Krypton can reach equivalent thrust levels to xenon around 10 mN for both configurations, nevertheless, a deterioration of the overall performance of about the 30% occurs —even for Hayabusa2, despite it shows a lower discharge loss. The former loss is mainly due to the increased neutralizer mass flow rate. The propellant demand on this device more than doubles for krypton vs. xenon, for comparable current levels. As a consequence, the redesign of the neutralizer cathode could be beneficial for krypton operation.

Also, it has also seen how krypton helps the stability of the high current mode for the DESTINY$^+$ ion source.

Additional further work must evaluate the effect of the propellant gas on the durability of the devices.

Lastly, the physical mechanisms responsible for the delayed drop in power absorption with increased mass flow rate for krypton with respect to xenon should be investigated. Especially for Hayabusa2, where krypton operation reaches higher current levels.

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References

1) Kuninaka, H., Nishiyama, K., Funaki, I., Yamada, T., Shimizu, Y., and Kawaguchi, J., Powered Flight of Electron Cyclotron Resonance Ion Engines on Hayabusa Explorer, *Journal of Propulsion and Power*, **23:2** (2007), pp. 544–551. doi:10.2514/1.25434

2) Kuninaka, H., Nishiyama, K., Funaki, I., Shimizu, Y., Yamada, T., and Kawaguchi, J., Assessment of Plasma Interactions and Flight Status of the Hayabusa Asteroid Explorer Propelled by Microwave Discharge Ion Engines, *IEEE Transactions on Plasma Science*, **34:5** (2006), pp. 2125–2132. doi: 10.1109/TPS.2006.876513

3) Tsukizaki, R., Koizumi, H., Hosoda, S., Nishiyama, K., and Kuninaka, H., Improvement of the thrust force of the ECR ion thruster μ10, *Transaction of JSASS, Aerospace Technology Japan*, **8** (2010), pp. 67–72. doi: 10.2322/tastj.8.Pb_67.

4) Nishiyama, K., Hosoda, S., Tsukizaki, R., and Kuninaka, H., In-flight operation of the Hayabusa2 ion engine system on its way to rendezvous with asteroid 162173 Ryugu, *Acta Astronautica*, **166** (2020), pp. 69–77. doi: 10.1016/j.actaastro.2019.10.005.

5) Tani, Y., Tsukizaki, R., Koda, D., Nishiyama, K., and Kuninaka, H., Performance improvement of the μ10 microwave discharge ion thruster by expansion of the plasma production volume, *Acta Astronautica,* **157** (2019), pp. 425–434. doi: 10.1016/j.actaastro.2018.12.023.

6) Ozaki, N., Yamamoto, T., Gonzalez-Franquesa, F., Gutierrez-Ramón, R., Pushparaj, N., Chikazawa, T., Dei Tos, D. A., Çelik, O., Marmo, N., Kawakatsu, Y., Arai, T., Nishiyama, K., and Takashima, T., Mission design of DESTINY$^+$: Toward active asteroid (3200) Phaethon and multiple small bodies, *Acta Astronautica*, **196** (2022), pp. 42–56. doi: 10.1016/j.actaastro.2022.03.029.

7) Kuninaka, H. and Satori, S., Development and Demonstration of a Cathode-less Electron Cyclotron Resonance Ion Thruster, *Journal of Propulsion and Power*, **14:6** (1998), pp. 1022–1026. doi: 10.2514/2.5369.

8) Kuninaka, H., Nishiyama, K., Shimizu, Y., and Toki, K., Flight Status of Cathode-Less Microwave Discharge Ion Engines onboard Hayabusa Asteroid Explorer, AIAA Paper, July (2004), 3438. doi: 10.2514/6.2004-3438.

9) Morishita, T., Tsukizaki, R., Nishiyama, K., and Kuninaka, H., Plasma parameters measured inside and outside a microwave-discharge-based plasma cathode using laser-induced fluorescence spectroscopy, *Journal of Applied Physics*, **131** (2022). doi: 10.1063/5.0071294.

10) Fazio, N., Gabriel, S., and Golosnoy, I. O., Alternative Propellants for Gridded Ion Engines, Space Propulsion Conference, 14th–18th May (2018), 102.

11) Fazio, N., Gabriel, S. B., Golosnoy, I. O., and Wollenhaupt, B., Mission Cost for Gridded Ion Engines using Alternative Propellants, International Electric Propulsion Conference, September 15th – 20th (2019), University of Vienna, Austria, 831.

12) Kim, Y., Lee, D., Doh, G., and Park, J., Performance comparison of xenon and krypton discharges in a 300 W-class Hall thruster, International Electric Propulsion Conference, June 19th–23rd (2022), Massachusetts Institute of Technology, Cambridge, MA, USA, 336.

13) Su, L. L., Marks, T. A., and Jorns, B. A., Investigation into the Efficiency Gap between Krypton and Xenon Operation on a Magnetically Shielded Hall Thruster, International Electric Propulsion Conference, June 19th–23rd (2022), Massachusetts Institute of Technology, Cambridge, MA, USA.

14) Esteves, B., Drag, C., Bourdon, A., and Alvarez-Laguna, A., Experimental and numerical investigation of a gridded ion thruster running with different propellants (I2, Xe, Kr, Ar), International Electric Propulsion Conference, June 19th–23rd (2022), Massachusetts Institute of Technology, Cambridge, MA, USA, 416.

15) Tsukizaki, R., Ise, T., Koizumi, H., Togo, H., Nishiyama, K., and Kuninaka, H., Thrust Enhancement of a Microwave Ion Thruster, Journal of Propulsion and Power, **30:5** (2014), pp. 1383-1389. doi: 10.2514/1.B35118.

16) Yamashita, Y., Tsukizaki, R. and Nishiyama, K., Investigation of plasma mode transition and hysteresis in electron cyclotron resonance ion thrusters, *Plasma Sources Sci,* **30:9** (2021). doi: 10.1088/1361-6595/ac243b.

17) Yamashita, Y., Tsukizaki, R., Daiki, K., Tani, Y., Shirakawa, R., Hattori, K., and Nishiyama, K., Plasma hysteresis caused by high-voltage breakdown in gridded microwave discharge ion thruster μ10, *Acta Astronautica*, **185** (2021), pp. 179–187. doi: 10.1016/j.actaastro.2021.05.001.

18) Goebel, D. M. and Katz, I., *Fundamentals of Electric Propulsion: Ion and Hall thrusters*, John Wiley & Sons, 2008.