Design and Performance Evaluation of Thruster with Anode Layer UT-58 for High-Power Application

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UT-58 is the first generation high-power thruster with anode layer (TAL) designed to evaluate the performance of argon as an alternative propellant for the high-power electric propulsion project RAIJIN. This study shows the first results of this evaluation in terms of thrust performance and discharge characteristics. Considerations of costs and storage of the propellant are also included. A power of up to 1.2 kW for xenon, and 2 kW for argon respectively, was applied to the thruster discharge. Regimes with weak and strong discharge oscillations were identified and related to the thrust performance. Anode efficiencies up to 60 % for xenon, and up to 24 % for argon were derived. From the correlation between discharge behavior and thrust performance, directions for further performance improvement are concluded.

Nomenclature

B	= magnetic flux density
E	= electric field strength
E_{ion}	= ionization potential
F	= thrust
g	= gravity of Earth
I_{D}	= discharge current
I_{sp}	= specific impulse
k	= tank-specific material constant
M	= molar mass
m_{t}	= tank mass
m_{p}	= propellant mass
$\dot{m}$	= mass flow rate
Q	= neutral particle flux
P	= Power
p	= pressure

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T	= temperature
u_e	= exhaust velocity
V	= discharge voltage
v	= spacecraft speed
Δ	= discharge current oscillation value
η_A	= anode efficiency
μ	= mobility
ϱ	= density
σ	= collisional cross section

I. Introduction

With the increase in electric power available on board of satellites, and the rise of scientific and political interest for further deep space exploration as summarized in the "Global Exploration Roadmap" (GER),[1] the urge for high-power space propulsion systems is evident. Technologies capable of ensuring a high thrust-to-power density, a high thrust efficiency, a long lifetime at a reasonable size and mass are obviously to be preferred from an engineering point of view. Among those, Hall thrusters remain the technology the most studied and the most promising to fulfill all the above-mentioned criteria.[2] However, when it comes to real space missions, aspects like feasibility of ground testing, procurement, costs, political restrictions, etc., play a strong role as well. Several propulsion systems are currently investigated in Japan for application in the GER[3] and the University of Tokyo has focused its efforts on the development of Hall thruster, that is, a thruster with anode layer (TAL), capable of not only providing a efficient and high-performing thruster head, but also considering the secondary aspects for eventual space applications. This project was dubbed RAIJIN - Robust Anode-layer Intelligent thruster for Japan IN-space propulsion system.[4]

In this study, the current progress in the development of high-power TAL in the framework of the RAIJIN project is shown on the basis of the 2 kW-class thruster UT-58 developed and tested at the University of Tokyo. The results will be used to evaluate the thruster design, and to derive criteria for the next thruster generations with eventual total power of about 100 kW.

II. Engineering model thruster UT-58

A. Propellant considerations

For decades, xenon had been the propellant of choice as a result of its small ionization potential at sufficiently high molar mass. Unfortunately, xenon is one of the rarest elements on Earth, and the current annual production rate will defy missions with high propellant demand. Alternative propellants were studied in the past, and are currently under investigation as well, to substitute xenon at reasonable thruster performance. Research so far has focused mainly on krypton as a valid replacement given an only slightly worse ratio of ionization potential and atomic mass, and Hall thruster were operated stably and at reasonable performance.[5–7] However, with Krypton still being one of the rarest natural elements, the procurement problem is only slightly improved.

Metal vapors were investigated as well and are currently under strong focus for SPT application due to the high-density storage capability.[8,9] It was concluded that the application of metal propellant, especially zinc, can yield a higher Δv at constant operation parameters, but lifetime issues are barely considered and thruster design was not adapted to the specific propellant in terms of channel shape and magnetic field configuration.

Other gaseous propellants tested in Hall thrusters were oxygen and atmosphere-like propellants[10–12] that showed instabilities in main discharge, questionable lifetime of the channel walls, and significantly reduced thrust performance. There are, thus, unlikely for high-power application.

Argon is an easy-to-handle low-cost propellant that is abundant in Earth's atmosphere and has, therefore, several advantages to the other noble gases. However, the ratio of ionization potential to molar mass and its storability are weaker than for xenon and krypton, and only a small Δv capability is to be expected.[9] Despite these disadvantages it was shown that in mission scenarios with high demand in propellant, the advantages can overcome the disadvantages even at lower thrust performance when regarding the total mission costs.[13]

The focus of this study was, therefore, to evaluate a high-power TAL with argon to estimate the validity of its application. Further, the thruster design and the operation conditions have a tremendous effect on the eventual performance and most thrusters up to date had been optimized for xenon, thus, design aspects for argon operation need to be newly derived from experimental data.
Following theoretical considerations, it is possible to estimate the changes that a substitution of xenon yields. As was shown by Kieckhafer and King,[14] assuming constant potential difference and constant average charge the exhaust velocity of argon ions will scale with the molar mass ratio by:

$$\frac{u_{\mathrm{e,Ar}}}{u_{\mathrm{e,Xe}}} = \sqrt{\frac{M_{\mathrm{Xe}}}{M_{\mathrm{Ar}}}} = 1.813. \tag{1}$$

The resulting thrust F scales similarly in theory if the mass flow rate is kept constant between usage of xenon and argon. This is, however, necessary to be verified experimentally.
The relatively high first ionization potential of argon yields that a significant fraction of the energy consumed in the discharge is used for ionization rather than acceleration. As derived by Kieckhafer and King, the fraction of ionization power will scale with power according to:

$$\frac{P_{\mathrm{ion}}}{P_{\mathrm{kin}}} = \frac{2 \cdot E_{\mathrm{ion}}}{g^2 I_{\mathrm{sp}}^2}. \tag{2}$$

The resulting fractions are plotted in Figure 1.

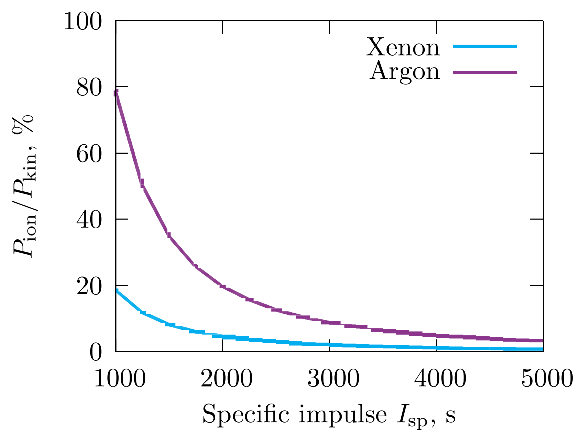


Figure 1: Thruster power fraction necessary for ion production as a function of specific impulse

It is obvious that argon can only be used efficiently if the specific impulse, and therefore the discharge voltage, is significantly high to avoid losses in propellant utilization.
Storability in space becomes a critical point when regarding the mass balance of the eventual spacecraft. The density of gaseous noble gases varies non-linearly with pressure as is shown in Figure 2.

The higher pressure will result in a thicker tank wall that translates into more mass on the spacecraft. Therefore, an optimum pressure can be found where the ratio of tank mass to propellant mass is minimal.[15] Design and material of the tank can still alter the number slightly, but for a qualitative comparison, the ratio can be derived as:

$$\frac{m_{\mathrm{t}}}{m_{\mathrm{p}}} = \frac{p}{\varrho} \cdot k, \tag{3}$$

where k is the material constant of the tank wall. For a typical value of 122,000 $\mathrm{m^2/s^2}$, the derived values are plotted in Figure 3.

Again, xenon shows much better properties than krypton or argon with a minimum mass ratio of about 4 % for a pressure of 8 MPa. Minimum values for krypton and argon are 17.9 % at 18.9 MPa, and 48.6 % at 15.4 MPa respectively. That is, for each kg of argon propellant at optimum conditions, another pound of tank mass would be required to store appropriately. It is therefore necessary to consider cryogenic storage to avoid massive tank structures. With a liquid density of about 1400 $\mathrm{kg/m^3}$ at temperatures below 90 K and

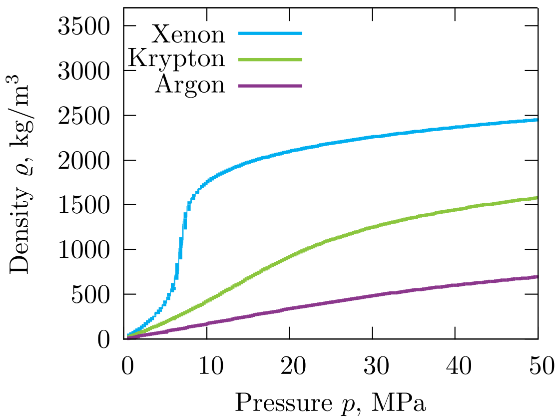


Figure 2: Gas density of noble gases as a function of storage pressure at T=300 K.

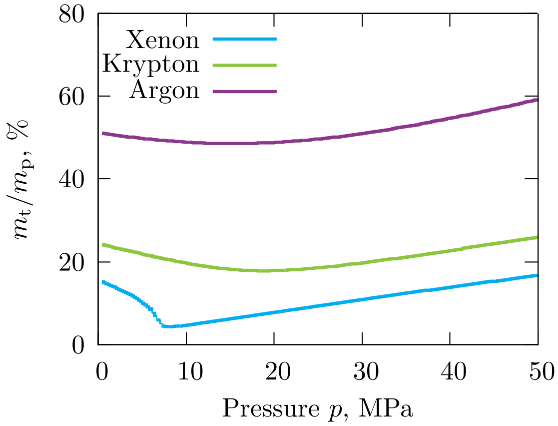


Figure 3: Ratio of tank mass to propellant mass for noble gases at T=300 K.

pressures of less than 1 MPa,[16] the tank mass reduces significantly to less than 1 % of the propellant mass, and the storage volume of the liquid argon is close to the optimum values for xenon. Hence, the economic disadvantage of cryogenic storage technology needs only to be compensated by the propellant cost in order to make argon the more reasonable choice in terms of mass storage.

B. Thruster design

UT-58 was designed to be able to handle both argon and xenon as propellant, but also to provide a flexible geometry and magnetic field configuration to evaluate the impact on the performance when operating with the different propellants. Additionally, the magnetic field can be configured to the recently established magnetic shielding configuration[17] to eventually reduce the erosion of the guard rings and the hollow anode, respectively. The anode has a mean diameter of 58 mm, thus the name UT-58, and is made of copper. The thruster head is depicted in Figure 4. For ground testing, a water-cooling system is used.

An inner and several outer coils form the magnetic circuit necessary for the operation of UT-58. They are made out of CEW, a nickel-plated copper wire with a ceramic insulation layer and a heat-protective plastic surface layer. Currents up to 6 A can be applied yielding magnetic flux densities of up to 80 mT on the center axis of the hollow anode. An Iontech hollow cathode is used for neutralization of the ion beam operating at a mass flow rate of 0.27 mg/s of xenon. Operation parameters are summarized in Table 2.

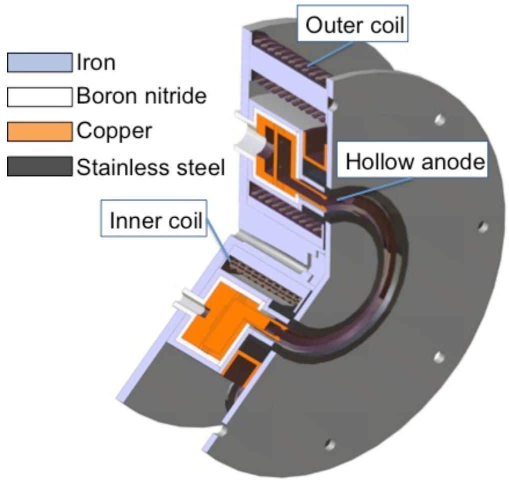


Figure 4: Section cut of UT-58 thruster with anode layer.

Table 2: Operation parameters of UT-58 thruster with anode layer

Parameter	Value
Discharge voltage V_D	up to 350 V
Mass flow rate $\dot{m}$	Xenon: 1.36-3.40 mg/s (1.0-2.5 Aeq) Argon: 1.23-2.90 mg/s (3.0-7.0 Aeq)
Magnetic flux density B	up to 80 mT

III. Experimental

A. Vacuum facility

For the evaluation of the thruster, two vacuum facilities exist within the premises of the University of Tokyo. The main facility comprises a ⌀ 2 m x 3 m long vacuum chamber equipped with two rotary pumps, a mechanical booster pump and diffusion pump. The total pumping speed of the first pumping stage (rotary pumps and booster pump) allows for a evacuation rate of 3,750 l/s whereas the diffusion pump enables an additional 37,000 l/s to create the necessary vacuum conditions. At an exemplary mass flow rate of 1.36 mg/s of xenon, a pressure of less than 3.7 mPa can be retained. Plasma diagnostic means as well as thrust performance measurements are feasible within this facility. A second smaller vacuum chamber allows for parallel experimental investigation of the thruster series. The ⌀ 1 m x 1.8 m long vacuum chamber is equipped with a rotary pump (50 l/s) and two cryogenic pumps allowing 18,400 l/s pumping speed for argon.

B. Parameters and target values

Disregarding the geometric impact and the magnetic field configuration for now, three main influential parameters can be considered for the operation of UT-58: discharge voltage, mass flow rate, and magnetic flux density respectively. For a first evaluation of the thruster design, and for the derivation of design criteria and directions for future studies, the influence of these three parameters is investigated for the different propellants. Therefore, the characteristics of the discharge and the thrust performance are measured. That is, the discharge current is measured, and the discharge oscillation Δ evaluated by:

$$\Delta = \frac{1}{\bar{I}_\mathrm{D}} \sqrt{\frac{\int_0^\tau (I_\mathrm{D} - \bar{I}_\mathrm{D})^2 \,\mathrm{d}t}{\tau}} \tag{4}$$

with the mean discharge current

$$\bar{I}_{\mathrm{D}} = \frac{\int_0^\tau I_{\mathrm{D}}\,\mathrm{d}t}{\tau}. \tag{5}$$

For the evaluation of the thrust performance, the thrust F is measured with a previously established thrust balance.[18] Specific impulse I_{sp} and anode efficiency η_{A} are calculated as follows:

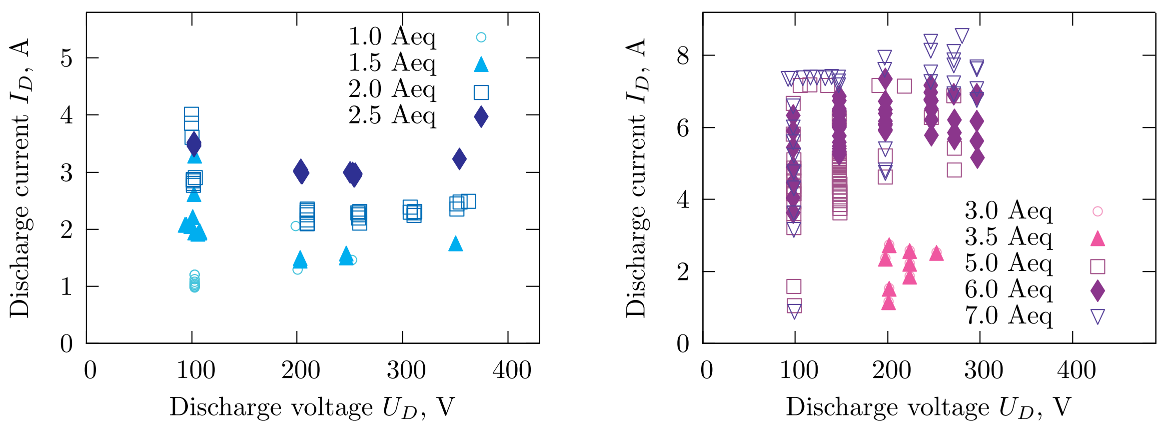
$$I_{\mathrm{sp}} = \frac{F}{\dot{m}g}, \tag{6}$$

$$\eta_{\mathrm{A}} = \frac{F^2}{2\dot{m}I_{\mathrm{D}}V_{\mathrm{D}}}. \tag{7}$$

IV. Results and discussion

A. Discharge performance

The discharge performance was measured for a variation in propellant (type and mass flow rate), discharge voltage, and magnetic flux density. Not all permutations of these parameters yielded stable discharges, and are therefore not included in the following discussion. The mean discharge current resulting from the parametric study is plotted in Figure 5.

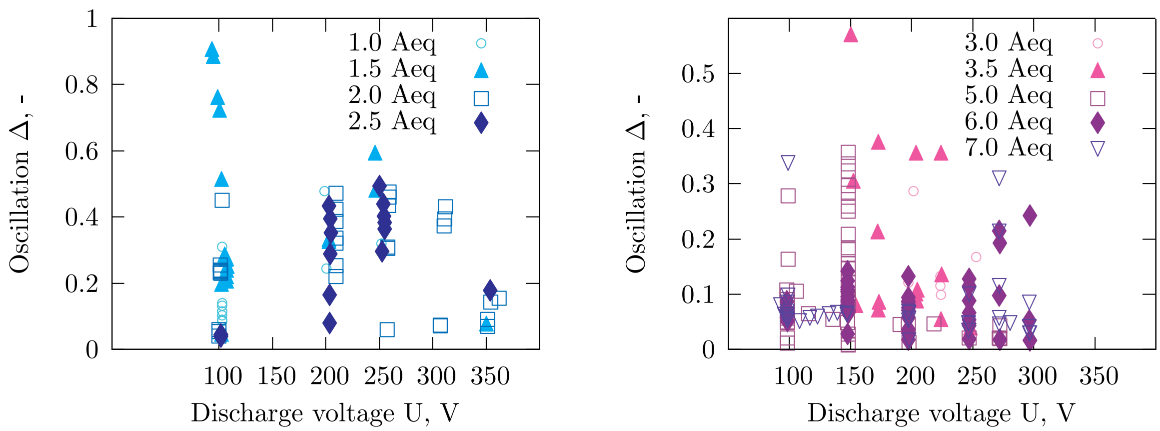


(a) Xenon (b) Argon

Figure 5: Discharge current characteristics as a function of discharge voltage, mass flow rate, and coil current

For xenon, discharge current values typically exceeded the equivalent from the mass flow rate, and hardly changed with a variation in discharge voltage. The influence of the magnetic filed is stronger at lower discharge voltages as can be seen in the strong variation of the current in the left part of Figure 5a. For argon, the results show a quite different behavior. The variation due to the magnetic flux density is much stronger resulting in a more scattered plot as shown in Figure 5b. In particular, there are many cases where the discharge current is below the mass flow rate equivalent indicating a less efficient propellant utilization. This is especially true for mass flow rates of 5.0 Aeq and lower.

Of particular interest for thrusters with anode layer is the oscillation of the discharge. This is generally seen the strongest disadvantage when comparing to stationary plasma thrusters (SPT) as those devices tend to have much smaller values. A strong oscillation can defy the discharge itself, can cause damage to the PPU and the thruster head, and might affect the thrust performance. Although it is envisaged to implement safety measures into the eventual PPU for the in-space application, it is evident for ground testing to keep the oscillation as small as possible. With the definition of Equation (4), the various experimental data were analyzed and the resulting oscillation values are plotted in Figure 6. It is evident that the magnetic flux density has a strong influence on the oscillation amplitude causing a scattering of the data points with values ranging from almost no oscillation to almost 1. Typical values for SPT are less than 0.2, therefore this threshold is considered safe for the further discussion. With increasing discharge voltage, the oscillation value decreases for both xenon and argon, which is favorable for later higher-power devices. In general, the discharges for argon propellant show smaller oscillation amplitudes but are more prone to other instabilities. Stability, independent from the discharge oscillation, remains a critical issue for usage of argon. Higher mass flow rates increase the stability significantly.



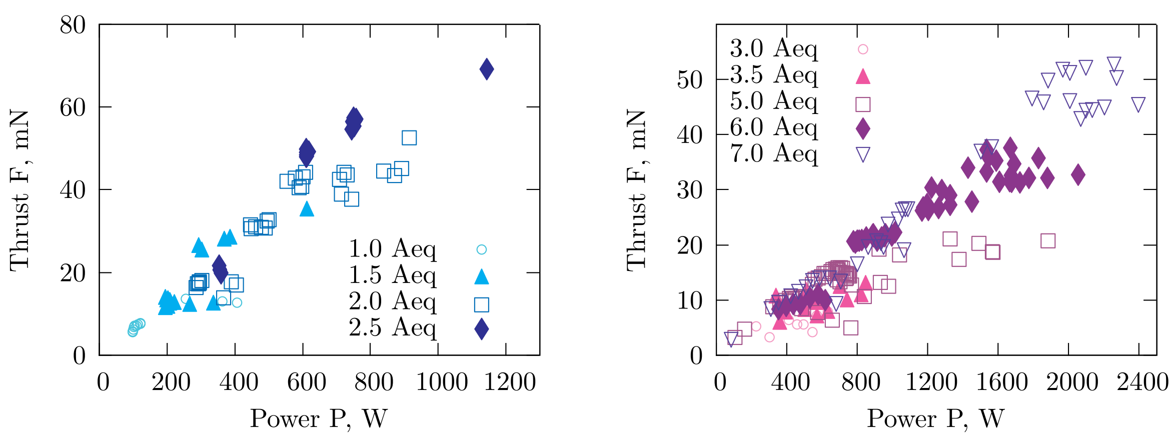
(a) Xenon (b) Argon

Figure 6: Discharge oscillation characteristics as a function of discharge voltage, mass flow rate, and coil current

From the figures, it can be seen that operation with small oscillation amplitude can be achieved under certain parameter permutations. It is, thus, necessary to evaluate whether these permutations also yield a considerably high thrust performance.

B. Thrust performance

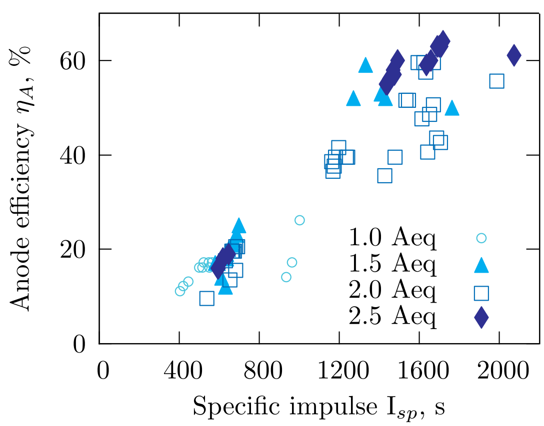
For the variation in discharge voltage, propellent flow, and magnetic flux density, the thrust was measured and is plotted in Figure 7. As expected, the thrust increases with power and mass flow rate showing roughly twice higher values for xenon than for argon at same power input. As the variation in magnetic flux density is affecting the discharge current as well, its influence is more difficult to grasp, but given the rather small scattering of data points, its actual influence on the performance might be inferior to the other parameters.



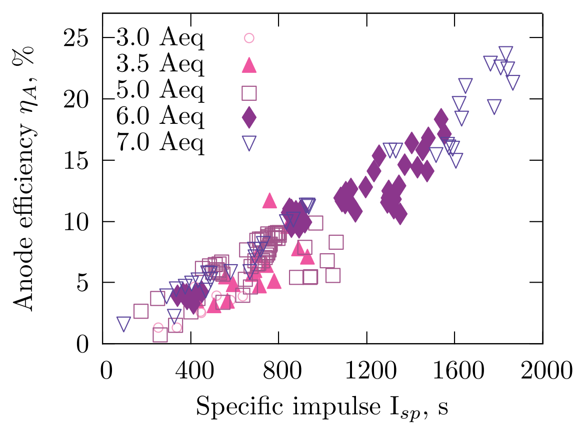
(a) Xenon (b) Argon

Figure 7: Measured thrust versus discharge power as a function of discharge voltage, mass flow rate, and coil current

It is interesting to note that around twice the power could be inserted into the argon-operating thruster for a similar mass flow rate (in absolute mg-numbers). That is, an eventual higher-power design could be built more compact saving volume and likely mass on the actual spacecraft. Unlike the theoretical expectation in Section A, the thrust is smaller for argon than for xenon. This is a direct result of the decreased propellant utilization efficiency.
This can be further realized by looking at the achievable total anode efficiencies and specific impulses plotted in Figure 8. For xenon propellant, the anode efficiency increases with discharge voltage up to values of around 60 %, eventually showing the typical knee in performance around 1600 s. With argon, UT-58 could realize values up to 24 % of anode efficiency with maximum specific impulses smaller than the xenon one. This again indicates a less efficient ionization, as the argon ions are reasonably lighter than xenon. However, with increasing discharge voltage and mass flow rate, the anode efficiency increases without signs of a soon flattening of the curve. This means that there is still potential in further increase of the anode efficiency. Due to current limitations in the experimental setup (maximum output voltage of the power supply, limitation by mass flow controllers and vacuum system), a further increase in power and mass input will remain a future work. It is, however, important to note that the efficiency is reasonably high to further consider argon as propellant for future thruster designs.



(a) Xenon



(b) Argon

Figure 8: Resulting anode efficiency versus specific impulse as a function of discharge voltage, mass flow rate, and coil current

With the efficiency and the specific impulse being subject to the variation of magnetic flux density, it is now necessary to combine the data obtained in the analysis of the discharge behavior and the thrust performance.

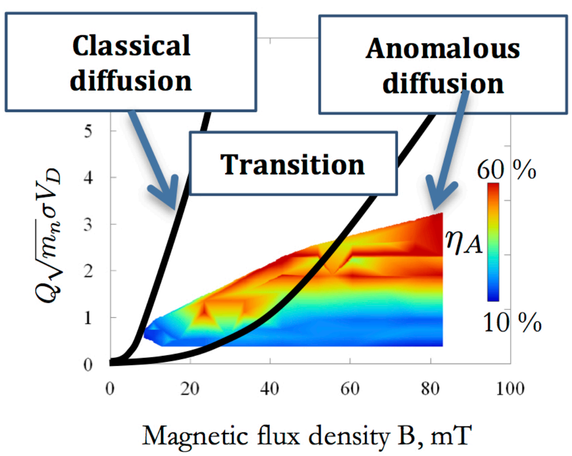
C. Evaluation of total performance

As the influence of the magnetic flux density is non-linear, further analysis of the data is needed with regard to the diffusion processes. From previous research, it is know that the oscillation behavior in TAL can be related back to the diffusion behavior of the free electrons.[19] Three regions can be observed - classical diffusion, anomalous diffusion, and a transition region in between which typically shows severe oscillations. Although the behavior can depend on the geometry and other factors, the main driving parameter is the magnetic flux density. That is, the differences in discharge oscillation observed in Figure 6 are a result of the changes in diffusion behavior.[20] Following the previous research, the electron velocity v_e can be described as:

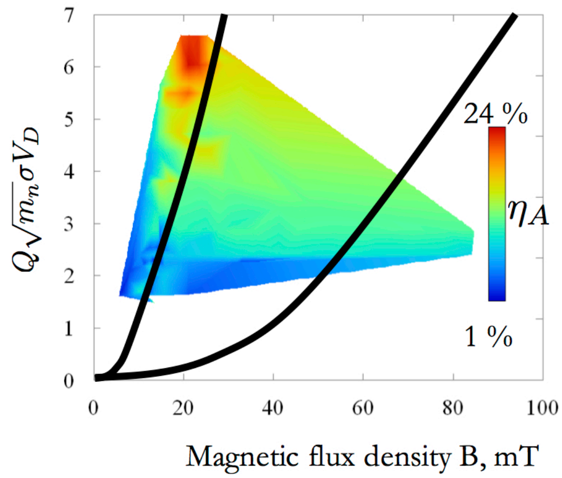
$$v_{\mathrm{e}} = \mu_\perp E \approx \frac{Q\sqrt{M_{\mathrm{n}}}\sigma V_{\mathrm{D}}}{B^2}, \tag{8}$$

with Q being the neutral particle inflow, M_{n} the molar mass of the neutral atom, E the electric field, and μ the electron mobility.
The above equation can be used to compare performance data from different propellants. Relating the oscillation values to the electron velocity yields information about the boundaries of the diffusion sections

as oscillations in classical and anomalous diffusion regions are small whereas strong oscillations occur in the transition region. Knowing these boundaries, it is possible to show the effect of the magnetic flux density by setting the RHS term of Equation 8 to the constant boundary, and mapping the anode efficiency for each propellant. The result is shown in Figure 9.



(a) Xenon



(b) Argon

Figure 9: Map of anode efficiency as a function of magnetic flux density and gas parameters. Boundaries between diffusion regions are tagged.

From the plots, it can be seen that most experiments for xenon happened either in a stable anomalous-diffusion region or in the unstable transition region whereas almost no classical diffusion behavior was observed. For argon, however, the best stable performance was observed in the regime of classical diffusion. That is, for a future increase in performance of the argon thruster, it is advisable to keep the magnetic flux density low and increase further the discharge voltage and the mass flow rate (the ordinate of Figure 9b) to obtain a stable, more-efficient operation. For xenon, in order to achieve a still better performance, an augmentation of the magnetic flux density might prove to be the better itinerary.

V. Conclusion and Outlook

UT-58 was designed and successfully operated at up to 2 kW of input power. Usage of xenon yielded around 60 % of maximum anode efficiency whereas argon yielded about 24 % of anode efficiency. It is expected that a further increase of discharge voltage and mass flow rate during the argon operation can improve further these performance data. It was shown that stable operation can be achieved for both propellants, but that the diffusion behavior is different. Although argon shows inferior thrust performance for now, the significantly lower cost and the abundance yield that argon can be a better candidate for high-power missions from an economical point of view. A case-to-case evaluation will be, however, necessary. To evaluate further the behavior of the argon thruster, numerical simulation and probe diagnostics are in preparation and will help to grasp the operation behavior.

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