

Investigation of transient behavior in water propelled Hall-effect thruster

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Piotr Fil * Emmanuelle Rosati Azevedo[†] Aaron Knoll[‡]
*Imperial Plasma Propulsion Laboratory, Imperial College London,
South Kensington, London, SW7 2BX, United Kingdom*

Hall thrusters are rapidly becoming one of the most popular types of propulsion systems. With the introduction of the Starlink constellation and growing ambitions for constant presence in cis-lunar space as a goal of the Artemis program, the role of this propulsion system will be even more prominent. Despite the industry-wide adoption of Hall thrusters, understanding of their transient behaviour is still limited. Within the scope of this research, instabilities present in the 10-100 kHz frequency range are investigated for different types of propellants. Comparison of thruster operation with krypton, oxygen and water as propellants provided the opportunity to determine the impact of different types of fuel on the thruster behavior and the conditions required for the onset of instability. It was determined, that different types of propellant have a varying threshold of voltage required for the instability to form, but it is present consistently for all cases under investigation. To properly explain the physics behind the instability, a 0D model of the thruster is developed and used to solve the dynamic behaviour. It was determined through simulation, that the thruster significantly interacts with the power supply, and it is necessary to consider the thruster coupled with the circuit to arrive at a proper solution. This was one of first attempts to develop a physics-based model of the thruster to apply in the full circuit modelling and its applicability was validated for thrusters operating with krypton, oxygen and water. The development of such models is of great importance for industry, as it enables more efficient design of filtering networks for onboard power supplies and direct drive modules, which would enable stable operation of thrusters, while fed directly from the solar panels.

Nomenclature

In this convention following variables are defined as marking properties:

V - velocity for continuum

v - velocity for particle

n - number density of charged particles

N - number density of neutral particles

B - magnetic field

E - electric field

U - electric field

f - density distribution function

ρ - charge density

q - elementary charge

e - elementary charge

t - time

*Undergraduate Student, Department of Aeronautics, Imperial College London, piotr.fil20@imperial.ac.uk

[†]PhD Candidate, Department of Aeronautics, Imperial College London, e.rosati-azevedo@imperial.ac.uk.

[‡]Reader in Spacecraft Engineering, Department of Aeronautics, Imperial College London, a.knoll@imperial.ac.uk

C - collision function
 ε_0 - vacuum permittivity
 ν - frequency of collision
 p - pressure
 m - mass
 T - temperature in either Kelvin or eV depending on context
 c_s - Bohm velocity $\sqrt{\frac{kT}{m_i}}$
 ω - gyrofrequency $\frac{qB}{m}$
 γ - heat capacity ratio
 R - specific gas constant
 I - current

Indices used in the notation:

i - ion
 e - electron
 n - neutral
 x - axial
 θ - azimuthal
 p - primary of transformer
 s - secondary of transformer
 C - across capacitor

Additionally, bold variables represent vectors, in most cases 3 dimensional, except for vector of density distribution functions, where number of dimensions is equal to the number of populations.

I. Introduction

Investigating instabilities in Hall-effect thrusters is relevant topic of research ever since they were introduced as a propulsion system. While they are often introduced as a DC propulsion system, when short timescales are considered their current traces become transient due to physical effects present in the plasma dynamics. This behaviour might interfere with the onboard electronics and it is necessary to understand it before thruster can be integrated into the satellite. For xenon and krypton which are fairly popular propellants, there is great amount of data from both experiments and numerical simulation, which can drive the design process. The same can not be said for water and oxygen, which are increasingly more popular subject for research. Thus aim of this paper is to try to record current traces of Hall-effect thruster operating with oxygen and water vapor supplied to the anode, compare the behaviour of both cases against the same thruster operating with krypton as a baseline result and finally develop a simple numerical model, with sufficient predictive capability to drive design of future experiments into investigation of said instabilities and possibly design of future thrusters.

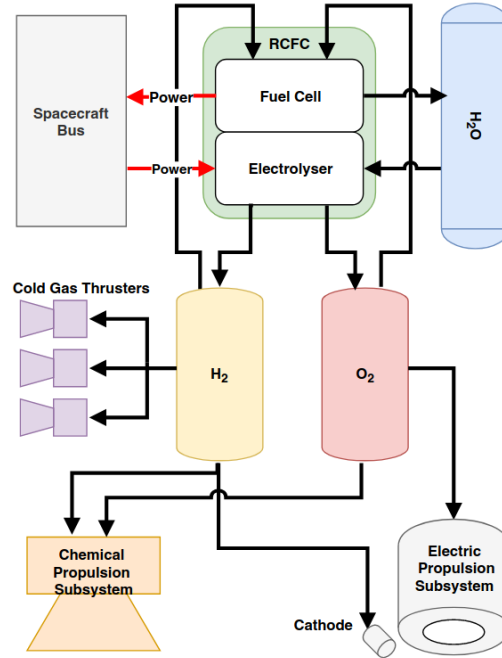


Figure 1: Architecture of propulsion system [1]

At Imperial College London, numerous activities aimed at developing and characterizing water-propelled Hall-effect thrusters were conducted. Initially, WET-HET thruster [1]–[4], was designed and then characterized for operation with oxygen supplied to the anode and subsequently, utilizing products of electrolysis as the propellants for both cathode and anode, in configuration resembling the one from Fig 1. Leveraging the lessons learnt from the experimental characterization of the WET-HET, the AQUAHET [5] was developed and characterized for operation with oxygen and water. In the previously conducted campaigns, focus was devoted to measuring thrust and no high frequency investigation of instabilities was conducted.

So far, only one attempt on characterizing transient behaviour of thruster operating with water was made and was published by Shirasu [6]. In that campaign very limited range of voltages was tested and thus the breathing mode might not have been captured. Thus, in this paper, broader range of voltages is considered, while the thruster is operated with both krypton and oxygen as propellants and data about the behaviour of the thruster is collected for such cases.

Primary objective of the project is to conduct the experiments aimed at measuring the current oscillations corresponding to the breathing mode. To expand upon successful collection of the experimental data, the secondary objective was to capture the physics of the observed behavior using a simple numerical model, which would enable prediction of the breathing mode onset conditions. For this purpose 0D model inspired by the one developed by Jorns [7] using the work of Barral [8], [9]. The model was then extended to include

energy model, which captures the interaction of the power supply electronics with the thruster. Analytical closure for the anomalous transport was applied so that modelled behaviour is closer to the actual physics and can be then compared against kinetic as well as fluid models to verify its validity against models which are more general, but solve the same physics, without introduction of some of closure terms.

II. Theory

In the original derivation consideration of various assumptions as the equations transitioned from kinetic to fluid model were presented. Those equations require further closure for the energy of electrons, which drives the reaction rate coefficient needed by the model. In initial attempts, it was assumed that the thermal energy is constant, but due to further observation made that electronics embedded in the power supply operate with similar frequency to the main oscillatory mode of the thruster, it became necessary to represent this coupling in simulations. For this purpose, as energy equation can capture I-V dependence for the thruster to voltage applied to it, it is added to close the system of equations. From that, Equations 1-3 are to be transformed into a 0D system, which still captures a breathing mode instability.

$$\frac{\partial N}{\partial t} + V_{nx} \frac{\partial N}{\partial x} = -\beta N n + \nu_w n \quad (1)$$

$$\frac{\partial n}{\partial t} + \frac{\partial(nV_{ix})}{\partial x} = \beta N n - \nu_w n \quad (2)$$

$$\frac{\partial(nV_{ix})}{\partial t} + \frac{\partial(nV_{ix}^2)}{\partial x} = \frac{e}{m_i} n E + \beta N n V_n \quad (3)$$

Assumption of purely advection-based transport of neutrals contradicts previous results where it was determined, that they also get accelerated as they propagate through the thruster. It does not change the conservation of momentum for the system though, as acceleration of neutrals occurs due to collisions with ions. Additionally, acceleration occurs more prominently in the ionization region, for which equations are averaged over the entire volume, due to less prominent timescales compared to the flow, with inlet velocity, determined using Equation 4 assumption of adiabatic flow expanding through an orifice to vacuum.

$$V_{ex} = \sqrt{\frac{2(\gamma + 1)}{\gamma}} \sqrt{RT_{in}} \quad (4)$$

For all working fluids under consideration, this results in inlet velocity is of order a few hundred meters per second, thus remaining about two orders of magnitude below the average velocity in ionization zone. For the motion of electrons, a closure term for the anomalous transport derived by Lafleur [10] which results in Equation 5 is applied to close the equations and remain closer to being self consistent.

$$\nu_a = \frac{\sqrt{6}}{24} \frac{\omega_e}{c_s n E_x} |\nabla(nT_e \mathbf{V}_i)| \quad (5)$$

With this form, there is no further requirement for experimentally derived constants. While there might be some discrepancy from the actual physics, results from the particle-in-cell modelling and experiments are in incredibly good agreement. It might indicate that this approach provides a better method of approximating anomalous transport and can be used as a base around which a more detailed closure model which accounts for higher order effects could be built.

To evaluate β it is also necessary to calculate closure, which would result in frequency of collisions for single electron. For this purpose, a Maxwellian distribution of electron velocities is assumed. Then for each temperature, which might exist in fluid β can be calculated by convolution of velocities with corresponding cross sections present in the population in range of 3 standard deviations. Using previously developed model, it is changed into analytical format given by Equations 6 - 8 where all functions are analytical to avoid piece-wise fitting.

$$\beta(T) = c_s(T) \sigma_{eff}(T) \quad (6)$$

$$\sigma_{eff}(T) = \frac{1}{c_s(T)} \int_{-\infty}^{\infty} \sigma(v) * v dv \quad (7)$$

$$\sigma_{eff}(T) = -AT^2 + B \exp\left(-\frac{C}{T}\right) \quad (8)$$

This representation has been widely adopted in the literature as a close approximation of the actual distribution. It is used in numerical simulations to reduce the access cost by removing the requirement to search through the array and conduct a local fitting. With those functions available for all the cross-sections [11], [12], it becomes feasible to capture energy losses associated with ionization events. In this investigation, only ionizing reactions were considered and extension to capture further non-ionizing behaviour will be conducted in further work. Coupled with 1D model adapted for fluid simulation [13] and applied previously introduced closure model for anomalous transfer it should be possible to resolve simulations with proper energy model, but would require further investigation into stability conditions.

Final model is given by Equations 9-11 that are derived by integrating neutral flow over characteristic line and in case of ion flow and ionization, by averaging properties over the thruster.

$$\frac{dN}{dt} = -\frac{\beta}{qAV_i}NI + \frac{\nu_w}{qAV_i}I + \frac{Q_0}{L} \exp\left(-\int_{t-\tau}^t \frac{\beta}{qAV_i}Idt\right) \quad (9)$$

$$\frac{dI}{dt} = \left(\beta N - \nu_w - \frac{V_i}{L}\right)I \quad (10)$$

$$\frac{dT}{dt} = \left(\nu_w + \frac{V_i}{L} - \beta N\right)T + \frac{2}{3} \left(\frac{q}{m_e \omega} \left(\frac{U}{L}\right) \left(\frac{\nu_e}{\omega} \left(\frac{U}{L}\right) + \frac{\sqrt{6}}{24} \sqrt{\frac{m_i T_e}{e}} \frac{\partial V_{ix}}{\partial x}\right) - \beta N \eta_i - \nu_w \eta_w\right) \quad (11)$$

This result extends the treatment by Barral [8], enabling self consistent solution of thruster model and enables simple coupling of the thruster with other components. This will be further explored in next section, which describes how thruster model was coupled with power supply to investigate it as a source of instability.

With the model of power supply previously, next step is introduction of the coupling with the power supply. For this purpose, it is needed to determine transient I-V characteristic of the thruster with some further variables representing the state space. To close this system, further Equations 12 - 13, for rate of change of voltage applied to the thruster and current flowing through capacitor are introduced.

$$\frac{dV_C}{dt} = \frac{1}{C}(I_s - I) \quad (12)$$

$$\frac{dI_s}{dt} = \frac{1}{L}(V_s - V_C) \quad (13)$$

This system of equations constitutes a differential delay equation, which can be solved using the same method as previously derived system, which described behaviour of the thruster subject to the constant voltage. This consideration should also be applicable for the fluid model in 1D, but in case of particle-in-cell model, further consideration should be given to the transient model of electron motion in the wiring, as it occurs on similar timescales as the smallest temporal features present in the system, in which electrons are being modelled using kinetic assumption. Required models are already being developed for precise simulations of microelectronics with semiconductors and are embedded in various implementations of SPICE [14].

III. Methodology

A. Experimental Facility

For the experimental part of the project, Boltzmann vacuum chamber at Imperial Plasma Propulsion Laboratory was used. It is large chamber (1.5 m in diameter and 2 m in length) used for testing electric propulsion systems, equipped with thrust balance designed for measuring forces in the range of millinewtons. There is also plenty of supporting equipment, such as power supplies, oscilloscopes and simple tools that enables

preparation and operation of the experiments. Chamber is equipped with three types of pumps used for staged creation of vacuum. Initially, roughing pump is engaged, then once free molecular flow is reached turbopumps are operated and finally, to keep sufficiently low pressure throughout the experiment cryopanel is used to capture remaining particles. The chamber routinely reaches baseline background pressures in the e-6 mbar range, and achieves high e-5 to low e-4 mbar values during thruster operation.

B. Thruster

Thruster used in the experiment is AQUAHET [15] designed with operation using water as propellant in mind. Target operating conditions for the thruster is 2kW and mass-flow-rate of 2 mg/s in typical operating conditions.

A 5 A-class LaB6-based orificed hollow cathode provided by Aliena Pte Ltd, the Hydrocat [16], is used. For the entirety of the tests it was placed at a 90° angle to the thruster, 42 mm downstream of the channel exit plane and 50 mm away from the channel centreline. It is operated with 15 sccm Kr, 1.5 A keeper current, and 5.5 A heater current.

Thruster was complemented with external support system, which included power circuit, with removable ballast inductor with inductance of 3 mH used to stabilize thruster, when operating with two power supplies. Another part of support system is feed-line that can supply either gases or water to the thruster. Gas feed-line is controlled with dedicated gas flow controller, while the water section has separate liquid controller, that operates in section, which is upstream of the point of transition to gaseous phase. Vaporization technique applied in this setup is long channel 0.1 mm in diameter, where as the result of wall friction pressure drops below the evaporation level. This leads to oscillatory behaviour of forming and collapsing water bubble, that with varying interface area leads to oscillatory behaviour of pressure downstream of the transition point.

C. Current probe design

Three separate methodologies were used to probe the anode current. The most simple of them was taking a voltage measurement across a shunt resistor. In this case, the resistor was constructed out of steel wires twisted around each other and was connected to the return path of the power supply. It was determined that the resistance of this shunt was 110mΩ meaning that for current of 10A it would experience voltage drop of 1.1V which is negligible compared to the total voltage across the thruster. Another option considered was the inductive current sensor, that operated on the principle of transformer, providing current reading proportional to the current. Constant of proportionality for this sensor was determined to be 0.05V/A enabling higher resolution of measurement than the value from the shunt. Main drawback of this probe was that it could not capture DC component of the current and signals below 10kHz were getting significantly distorted. Finally, an Elditest current probe (model nb. CP6550) was used. The Elditest probe relied on a Hall sensor coupled with an operational amplifier for the detection of the hall sensor voltage. It had issues with capturing signals above 50kHz as capacitance of the sensor was interfering with the Hall sensor measurement, but when data from all 3 sensors was combined it provided coupled dataset, which could be used to better quantify error estimate and remove impact of noise for each singular sensor.

In the design process for the shunt resistor initial idea was to use 15Ω resistors bundled together to form 3Ω shunt, which would lead to voltage drop of 30V when 10A current was applied. This caused a grounding issue, when inserted into grounding path of power supply, as it decoupled anode and cathode grounds, causing chaotic behaviour and unstable operation of the thruster.

For the inductive probe the design process was considerably more complex. In this case, rough inspiration was taken from how the Tektronix P6022 probe [17] was designed and operated. Due to tight budget constraint it was impossible to purchase such probe, so using its documentation an attempt was made on reconstructing similar device using simple electronic components and calibrating it after the manufacturing phase. In the probe design, inductor with 20 turns wound around a ferrite core with connected resistor. Voltage across the resistor is proportional to the current, which in turn is proportional to the current in the wire, for the range of frequencies determined to be from 10 kHz to 4 MHz. This bandwidth is well suited for testing for the breathing mode, but would fall short for capturing higher frequencies of oscillation. In Fig. 2 both schematic and the manufactured probe is presented. Process for determining the bandwidth will be described in the next section and instructions regarding how probe could be adapted to higher bandwidth by changing the oscilloscope to 50Ω input impedance.

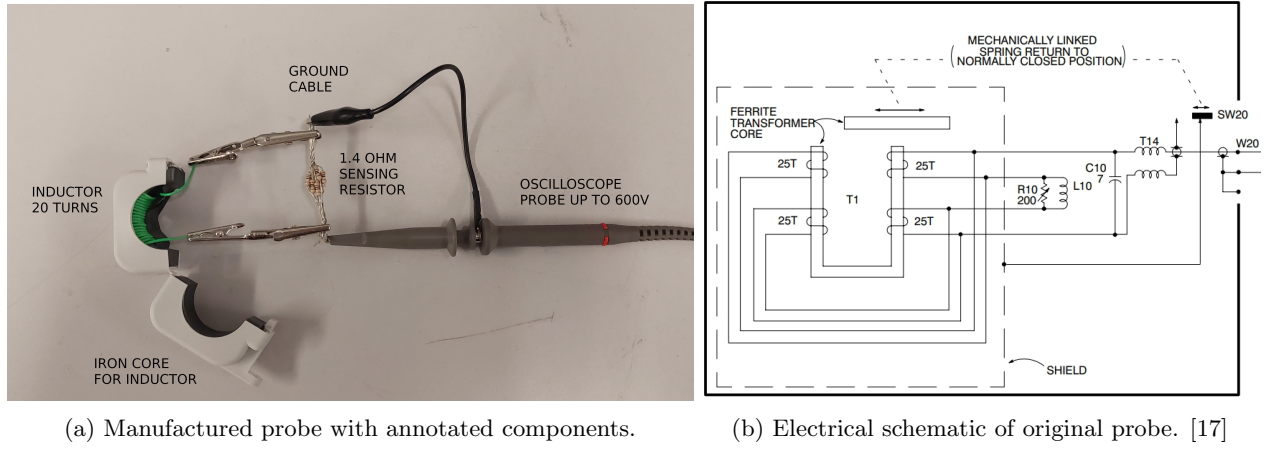


Figure 2: Probe electronic schematic and manufactured design.

D. Current probe calibration

In the calibration process, sinusoidal signal of varying frequency was applied to the probe and both amplitude and phase shift of current in the probe with respect to current in tested conductor was investigated. To provide the voltage, signal generator capable of operating in range 10Hz to 20MHz was used. During the tests, current in the reference conductor was measured across a resistor connected into a grounding path of this circuit and measured using the oscilloscope. For the sensor, another voltage probe was used to sense the voltage change across the resistor connected with sensing inductor. Then, by sensing both voltage signals, magnitude of oscillations for both were determined and phase shift was identified. In the investigated case, proportional response ranges from 10kHz to 4MHz, as mentioned previously. In low frequency regime main limiting factor is low coupling in between the test cable and coil with 20 turns. On the higher end, reason for discrepancy is increasing loss due to core. In the range of usability, scaling for the probe was determined to be 0.05V/A by fitting scale between input and output plateau. For more sophisticated probe, better materials could be used, but within this project it provided sufficient quality of the results.

E. Experimental procedure

For the purposes of this project, the anode current trace needed to be collected at various operating conditions. For this purpose, shunt resistor with an oscilloscope probe across it is inserted into the grounding path of the experiment and inductive probe is inserted into the circuit. Past this point typical sequence of operating the thruster was followed:

1. Set mass flow rate of propellant to the desired value, while keeping manual valve on anode feedline closed.
2. Apply ignition bias voltage to anode with the current set to a 0.5 A limit.
3. Open manual valve on anode feedline.
4. Set the magnet current to 2.5 A
5. Switch into voltage controlled mode.

At the point when magnets were turned on and thruster was engaged in voltage-controlled mode, it was possible to move into further stages. After the successful ignition, data acquisition process can be initiated and current traces are collected for various operating points along the I-V characteristic curve of the thruster. Furthermore, detailed analysis of sources of uncertainty should be conducted in order to ensure, that collected data is properly interpreted and reported.

F. Data acquisition

Strategy for collecting the data is to use an oscilloscope in manual data acquisition mode, which is engaged by the operator every time, when measurement needs to be taken. Initial attempts to automate this process were made, but it was observed that there are numerous behaviours of the thruster, which prevent simple methods of deciding to take measurements from being effective. The most significant issue is drift of performance point with increasing temperature. To account for it, as it behaves slightly differently from measurement to measurement, it was decided that the most efficient way to conduct experiments would be to manually engage the oscilloscope. List of steps for each measurement follows:

1. Set the desired operating voltage.
2. Trigger measurement on the oscilloscope.
3. Repeat for all the voltages of interest.
4. Save data to USB stick and copy to PC.

After this process is finalized, data processing can be initiated. It was determined, that for the purpose of this project timeseries which includes data from 1ms of operation will be sufficient to conduct the desired operation. Sampling frequency of the oscilloscope was set at 5MHz enabling reasonably good resolution for capturing breathing mode and edging at the top limit of frequency for inductive current probe. It was the same for all the probes used during the campaign, both shunt resistor and inductive probe performed well while acquiring the data, but in case of COTS probe higher order harmonics were distorted and dissipated due to capacitance of Hall-sensor embeded in the probe.

G. Sources of uncertainty

Experimental setup outlined above exhibits numerous sources of uncertainty, which need to be understood and accounted for when analyzing the data. They in most cases stem from either unavoidable properties of physical setup, such as operation characteristics of vacuum chamber and thruster. The measurement setup has also some manufacturing defects and unknowns, which can present themselves in the data. List of all identified sources and proposed mitigation strategy is presented if applicable:

- Variations in background pressure in vacuum chamber - might affect frequency of electron neutral collision, thus affecting operation of the thruster. Should be monitored for all experiments.
- Instabilities in water feed-line - similar to the previous point, transients too slow to interfere with the breathing mode at timescales of interest.
- Power supply to thruster coupling - affects the breathing mode, as switching frequency is of the same order as breathing mode, requires consideration in modeling to properly compare experiment with theoretical results.
- Thermal effects on the shunt resistor - coupling collected data with other current sensor to capture discrepancies of collected current traces.
- Out of range operation of inductive sensor - coupling collected data with other current sensor to capture discrepancies of collected current traces.

It is necessary to conduct the same type of analysis for every new experimental setup, as changes in the equipment are likely to introduce other sources of uncertainty.

IV. Results and discussion

To contextualize the results, first part, which will be presented in this section are I-V characteristics given in Fig. 3, which were taken during the testing campaign. There were 2 attempts to run test with krypton, once it was proven that indeed, breathing mode can be observed for such case and in the second instance mass-flow-rate was matched to the conditions, at which breathing mode was observed, when thruster was

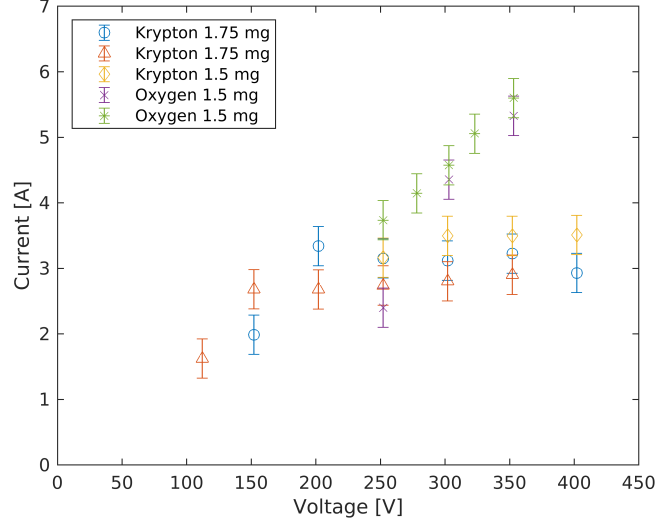


Figure 3: I-V Characteristics from the test campaign.

operated with oxygen. Also, for oxygen, there was one repeated run, to ensure that the result could be replicated. One standard deviation in terms of noise level was considered as the measurement uncertainty.

Operating conditions had to be varied from the case to case, it was mainly due to issues encountered with the cathode. To facilitate repeatability of the results, those data are reported in Table 1 for each of the curves collected during the campaign. Collected data are cathode keeper parameters and magnet current.

Name of the dataset	Keeper Current [A]	Keeper Voltage [V]	Magnet Current [A]
Krypton 1.75 mg/s 1	1.5	25	2.5
Krypton 1.75 mg/s 2	1.5	28	2.5
Krypton 1.50 mg/s	1.5	22	2.5
Oxygen 1.50 mg/s 1	1.5	27	2.5
Oxygen 1.50 mg/s 2	1.5	23	2.5

Table 1: Operating conditions during the test campaign.

To investigate, the behaviour of the breathing mode, points at the characteristics beyond the knee-point were taken, as the most likely location of the breathing mode. For krypton, the results are presented in Fig. 4 where both raw and processed traces are plotted for both experiment and numerical simulation.

Similar process was conducted for oxygen. In this case the knee voltage was not captured and IV is still increasing when the breathing mode forms. In simulations it was determined, that there is significant impact of the losses on how the breathing mode behaves and further investigation with higher fidelity models has to be conducted to fully understand the underlying physics. Data is visualized in in Fig. 5 where again experimental and numerical results are compared.

In the first part of experiment, testing with krypton was conducted, to identify possible sources of uncertainty, that might be present within the model. Breathing mode was observed to be forming, whenever the system reached point beyond the knee on I-V characteristic. It can be understood, as thruster reaching its saturated condition and the instability occurring as a result of population tending towards higher current than can be feasibly sustained. One of prominent features seen in the data are high uncertainties of the I-V curve data. It can be attributed to thruster operating in the state, where thermal equilibrium is not yet achieved, thus causing drift in terms of the magnet properties, which deteriorate with increasing temperature. To conduct testing, where better control over those parameters can be achieved.

To facilitate better tracking of the curve at the measurement time, data can be gathered with the oscilloscope and thus facilitating automated measurements of I-V transient behaviour by averaging out noise

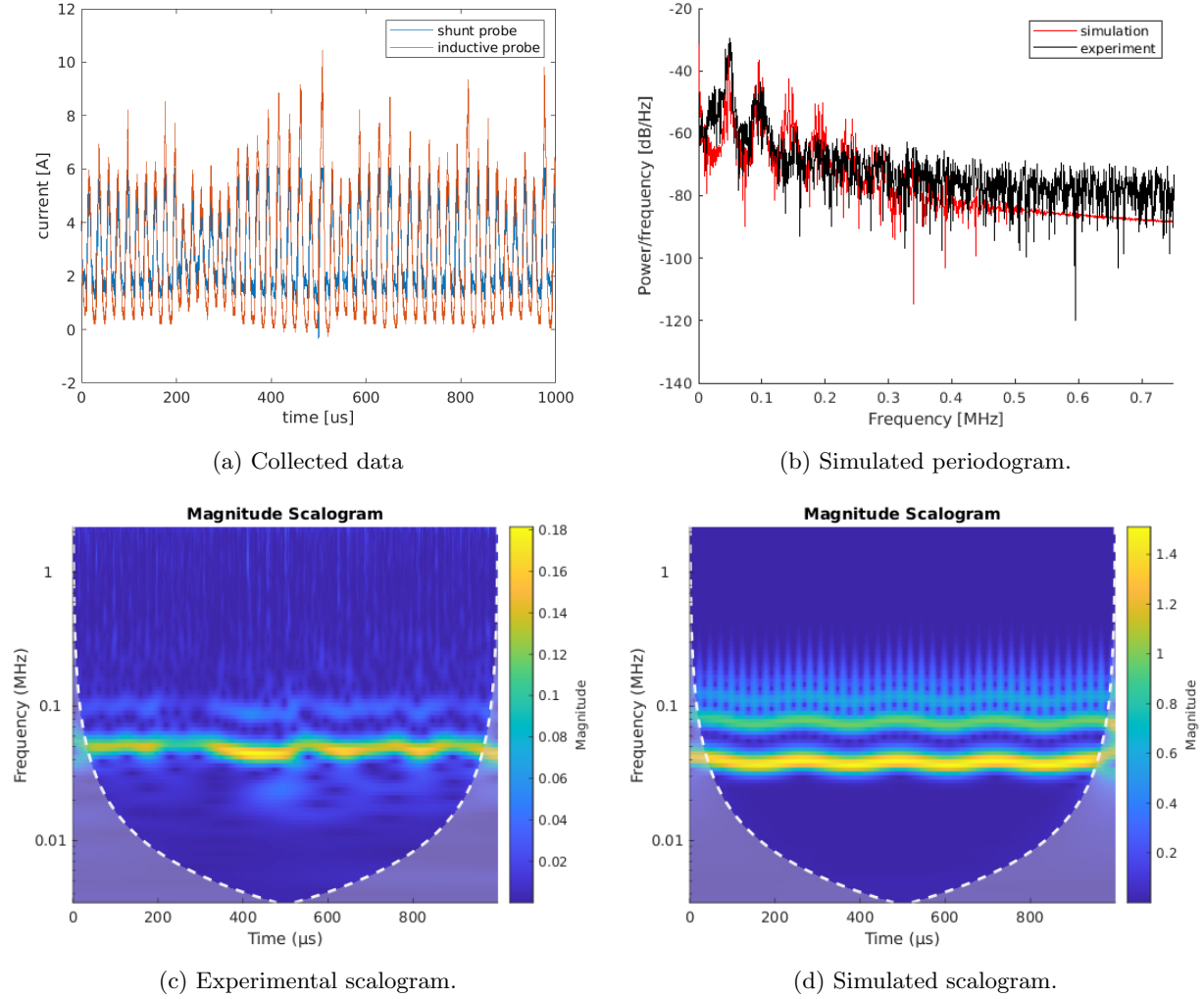


Figure 4: Breathing mode with krypton.

in collected oscilloscope data. For the case under consideration though, it was required that breathing mode is resolved with sufficient resolution, that timescales relevant to thrust measurement could not be captured.

For the data collected using krypton very nominal trace was collected. It was determined that frequency of the breathing mode oscillation is 48 ± 1.5 kHz where as the measure of uncertainty range in which magnitude decreases to half of the peak magnitude. In the data drifting over time was observed, that was later attributed to the effect of power supply on the circuit. For the purpose of this investigation, simplified fluid model of thruster coupled with the electrical model of power supply was created. It enabled rapid iteration of the model and resulted in capturing idealized breathing mode. Because of this idealization, no noise was present and thus harmonics, which are not smeared in this case can be clearly seen. In the measurement taken with the shunt probe, the results were cut off at the peaks of response, what was attributed to the accidental setting of x10 attenuation, which presents itself in this manner.

With the same approach, as for krypton data was collected and processed for oxygen. In this case, frequency of oscillation was 25 ± 1 kHz which was quite unexpected result, given that it was previously assumed, that with decreasing propellant mass, frequency of the breathing mode should increase. In this case, effect of coupling between power supply and thruster was less pronounced than for the case, when it was operated with krypton. It can not be determined from currently conducted simulations, why it was the case, and further sensitivity studies would have to be conducted to fully understand the coupling. Additionally, model might be improved when higher order reactions are added, so that more complete loss mechanism is

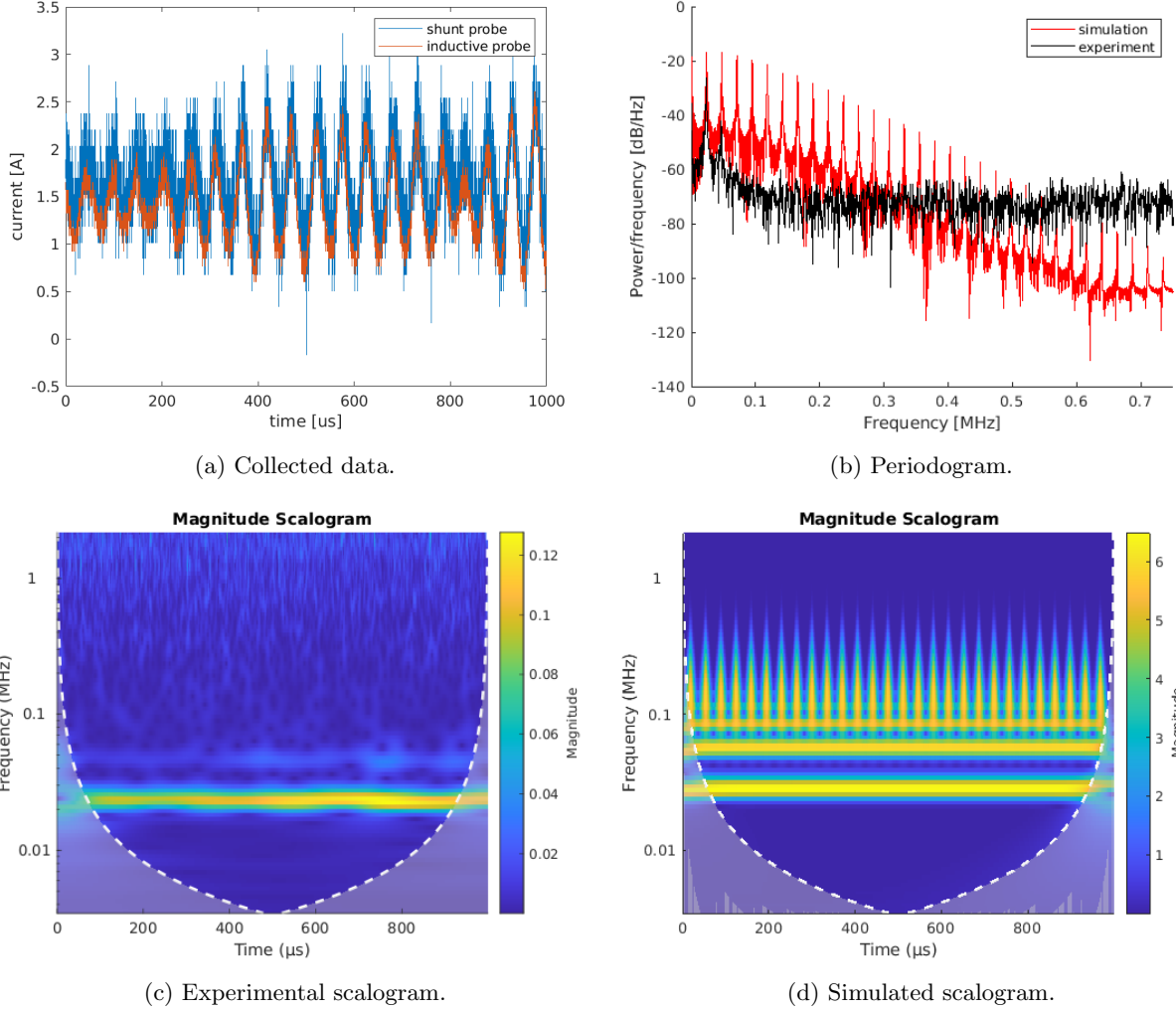


Figure 5: Breathing mode with oxygen.

resolved. Comparison against higher order models would be needed to fully confirm or disprove this idea.

In the data series which were collected it was observed, that breathing mode is a common phenomenon and it can also exist in thrusters, which are operated with propellants of relatively low molecular weights, such as oxygen. Additionally, 0D model of the thruster was developed using the most modern approach to modeling the electron mobility, using purely physical closure terms. This constitutes a large progress, as it enabled resolving the breathing mode and at a same time enables extremely simplified models, which can approximately satisfy the energy conservation. While some losses are still being neglected, it is becoming more feasible to construct simple engineering models, which can be used during the design process and validated with more complex ones as well as experimental results.

V. Conclusion

Within the scope of the conducted project, significant progress was made towards furthering understanding of the transient behaviour of water-propelled Hall-effect Thrusters. Building upon the research, which was previously conducted into this topic, an experimental campaign was planned and executed to collect data which would then drive the computational efforts into predicting how transient behaviour of a thruster operating with water differs from conventional propellants. During the campaign, data was collected for a thruster operating with krypton as the control case, oxygen for which literature data is non-existent and

which is also of great importance from the perspective of thrusters operating with electrolyzed water. Both propellants were investigated in wide range of voltages and for all of test cases, when sufficiently high voltage was applied, breathing mode formed. It could be observed, that for both oxygen and water, considerably higher voltages were needed to enter this regime of operation. This can be attributed to higher losses associated with nonionizing reactions, which dominate in those conditions, and do not allow for the ion population to saturate and thus enter predator-prey relation. It means, that for low voltage operation, which is becoming increasingly popular, with the push towards direct-drive thrusters, this type of oscillation will not be present, but the cost for it will be thruster losing considerable fraction of power to dissociation of propellant.

During the experimental campaign, it was shown, that breathing mode is phenomenon likely to be present across wide range of propellants, whenever thruster is operated at sufficiently high voltage to facilitate depletion of neutrals and subsequent reduction of ionization rate. For more complex reaction mechanisms, there might be some further complexity introduced by interactions of multiple species, but for the scope of initial investigation, simple model, which included only one ionization method and no dissociation mechanism, proved to be sufficient to capture relevant features. To completely resolve some of non-ideal behaviour present in the simulation, model of power supply was needed. From that, it is recommended for future research focused on instability analysis, to characterize all the power supplies present in the circuit and investigate their impact on the setup, so that false positives forming due to oscillating energy input from power supply can be mitigated. This, together with all previously mentioned aspects of the process, should drive the development of Hall-effect thrusters, which operate on exotic propellants further and provide guidance and lessons learned for the future.

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