Technique for Two-Frequency Optimization of an ECR Magnetic Nozzle Thruster

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The experimental setup and optimization techniques are presented for an upcoming test campaign to improve the performance of a low-power Electron Cyclotron Resonance (ECR) thruster using multi-frequency heating techniques. Recent experiments at ONERA using ECR plasmas in a magnetic nozzle thruster have demonstrated thrust efficiencies over 10%. The goal of the work presented here is to improve upon these results by using custom power input wave-forms, thus enabling rapid optimization without physical alterations to the thruster design. Specifically, this experiment is designed to implement two-frequency heating to increase thrust while average power and mass flow rate are held constant. While this technique has been utilized to improve the yield and stability of ECR ion sources, it has not been employed in thruster design. The thruster design, microwave signal generation and power input, including a new wireless power coupler, and thrust stand are described in detail. The optimization algorithm and techniques for an upcoming test campaign are presented.

I. Introduction

Low power magnetic nozzle thrusters promise several features that make them ideal for small satellite applications. They offer simple operation, with only a single required power supply, and lack the often life-limiting neutralizer cathode that is required by most mature Electric Propulsion (EP) technologies. However, performance to date has typically been much lower than more established EP thruster designs, with low power thrust efficiency typically on the order of 1% [1]. Magnetic nozzle thruster designs using Electron Cyclotron Resonance (ECR) heating, in particular those designed at Office National d'Etudes et de Recherches Aérospatiales (ONERA), have shown great promise in overcoming the historically poor performance. Their recent experiments have demonstrated thrust efficiency over 10% and 1000s during a 50 W test, while previous Helicon thruster experiments have typically seen efficiencies under 2% at these power levels [2–6].

Magnetic nozzle thrusters generate force by converting the random thermal energy of a plasma, typically generated by externally applied radiofrequency (RF) or microwave fields, to directed kinetic

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energy. In the case of ECR, heating is a achieved when the frequency of the applied electromagnetic wave matches that of the natural electron cyclotron motion that occurs when a DC magnetic field is present within the plasma. This condition can be described mathematically as $\omega_{in} = eB/m_e$, where e is the electron charge, B is magnetic field strength, and m_e is the electron mass. Because the DC magnetic field is not constant is space, typical ECR discharges contain a single resonant surface over which the plasma absorbs most of its energy[7]. The hot electrons generated through ECR are then expelled through an expanding magnetic nozzle, pulling the ions with them in an ambipolar diffusion process. Finally, the plasma must detach from the magnetic field lines in order to generate useful thrust. This process has been characterized in many magnetic nozzle thrusters, but to this day is not well understood and is the subject of ongoing research[8–10].

ECR magnetic nozzle thrusters have a long history in the EP community, with many earliest thruster concepts built around the technology[11]. Though there was some success operating these thrusters at kilowatt power levels, the bulky microwave sources of the time prohibited their use on satellites, and research on this topic declined sharply as gridded ion and hall effect thrusters matured[12]. While not suited for spaceflight at the time, ECR technologies have seen extensive use in both plasma processing reactors and as ion sources for particle accelerators[13,14]. Since the 1960's, the miniaturization of microwave sources has enabled ECR to once again become a viable technology for both medium and small scale satellites, and it has been recently used as the ionization source for gridded ion thrusters in deep space missions[15].

The goal of the experiment detailed in this paper is to continue to improve ECR magnetic nozzle thrusters using optimization techniques inspired by the ECR ion source technology, namely two-frequency heating. As such, this paper is organized in the following way. In Sec. II, we outline different design parameters that can be tuned to improve ECR performance and explain why two-frequency heating was selected for the initial optimization experiment. In Sec. III, we describe the optimization algorithm used in the experiments, and in Sec. IV we present the experimental setup including the thruster, vacuum chamber, thrust stand, and trial point testing techniques used in the experiments.

II. Optimization Design Parameters: Two-Frequency Heating

Selecting proper design variables for an optimization experiment can be a challenging endeavour, particularly when the underlying physics is poorly understood. As such, we turn to previous research on ECR plasmas to inform our design choices. Several techniques have been developed to enhance the performance of ECR plasma sources over their multi-decade history. These techniques are largely dependent on the end use, whether it be process uniformity and selectivity in processing plasmas, or highly charged ion yield in the case of ECR ion sources. The methods developed include both physical design changes, such as magnetic field topology, wall material selection, and waveguide coupling, as well as changes to the input waveforms, which will be the focus of this study.

In the EP community, work on developing ECR powered gridded ion thrusters has yielded several new magnetic field designs and microwave antenna configurations. These new features have generated increased plasma density as well as reduced erosion rates in these thrusters, and have enabled their use in deep space missions[16]. More recently, research performed by ONERA on an ECR magnetic nozzle thruster has shown that small geometric changes to the inner antenna and thruster walls can have profound impacts on performance, with thrust efficiency increasing over 400%[17]. These performance changes are not easily captured in simple simulations, thus necessitating a large number of experiments to find optimal design points[18].

While geometric design studies have yielded great improvements in device performance, changing these parameters often comes at a great cost, both in terms of testing time and fabrication expenses.

As such, it is highly desirable to find design variables that do not require physical changes be made to the thruster geometry. The primary such parameter is the input RF or microwave waveform that is supplied to the plasma. While this variable has remained largely untouched in EP studies, there have been many techniques developed for plasma processing and ECR ion sources that rely on tailoring the input waveform. These include pulsed power techniques used in plasma processing and multi-frequency heating, a common practice in ECR ion sources since the 1990s[19,20].

Given the virtually unlimited number of variables that can be tuned when creating a custom input waveform (frequency, duty cycle, modulation type, bandwidth to name a few), we intentionally choose to limit the scope of our initial optimization experiments to focus on two-frequency heating. This technique was first successfully implemented in the Lawrence Berkeley Laboratories Advanced ECR ion source in the 1990s, and is now standard practice in highly charged ion sources[21–24]. Simply stated, two-frequency heating adds a second resonance zone to the discharge, as shown in Fig. 2 (b). By increasing the volume over which the electrons are efficiently heated, it has been postulated that power coupling efficiency can be enhanced. This effect increases the density of hot electrons, which in turn leads to better ion source performance. Subsequent experiments showed that the addition of a second frequency dampened the discharge oscillations by suppressing kinetic instabilities typically present in ECR ion sources[25]. The underlying physics of these improvements are still not fully understood[26]. These experiments did, however, demonstrate just how sensitive ECR plasmas are to small changes in input waveform with changes of only a few MHz significantly modifying the output ion beam of a 14 GHz experiment[24,27]. Although the operating regimes of the ECR ion sources for highly charged ions are quite different than those of ECR thrusters (i.e. much higher frequencies and magnetic field strengths), the experiments indicate that two-frequency heating may be a promising starting point for ECR thruster optimization.

By using two independent frequencies and holding the total input power constant, we have opened the design space to 3 independent parameters: f_1, f_2, and P_1/P_2. Here, f_1 and f_2 are the two input frequencies, and P_1/P_2 is the ratio of their powers. These input parameters can be tuned at different total power and flow rate settings to find optimal operating conditions at alternate thrust levels and specific impulses. By optimizing at several set points, we can generate a Pareto front of optimal parameters such as that shown in Fig. 1. This information would allow the thruster to be operated more efficiently across a wider envelope of mission-dependent operating conditions.

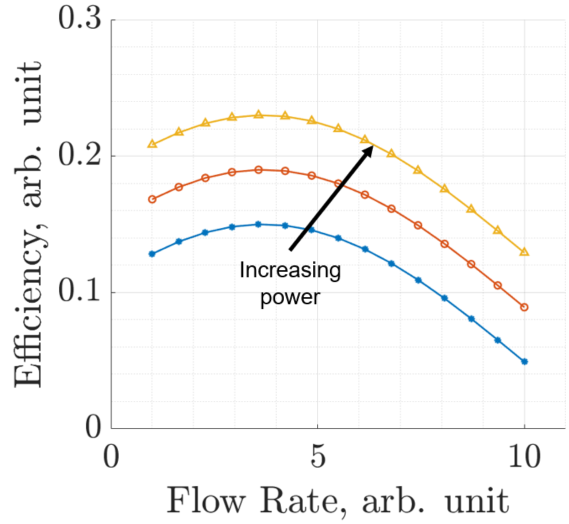


Fig. 1 Hypothetical Pareto front showing the highest efficiency operating points at various flow rates and power levels. By optimizing the input waveform at these flow rates and power levels, we can potentially widen the operating envelope of the thruster.

III. Optimization Algorithm

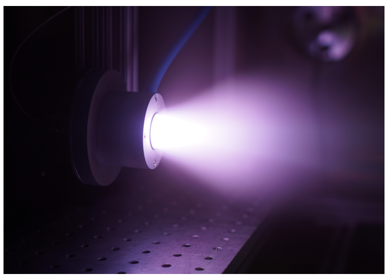
As we will show in Sec. IV, measuring thrust at each new test point can take several seconds. Furthermore, data from ECR ion source experiments indicates that the system may be very sensitive to changes in input waveform. Thus, by introducing three free parameters, we have already expanded the design space to an extent that a brute force approach cannot be executed in a realistic time frame. We therefore require a more intelligent strategy for selecting new test points. Typical optimization algorithms are likely insufficient for this task as there can exist several local optima and the data produced by the experiment is often noisy. However, there exist several gradient-free non-convex optimization techniques that are well-suited for this type of data. These types of optimization algorithms have been successfully employed in fusion experiments in which tens to hundreds of parameters can be tuned between each run[28].

With this in mind, we have selected a Bayesian optimization solver for the initial ECR experiment. This algorithm works by creating a surrogate model of the output function based on a predetermined set of initial data points. It then uses an acquisition function incorporating the surrogate model to select new test points. The surrogate model is then updated with the new data using a Bayesian posterior probability, and the acquisition function is called again. This procedure is repeated until a stopping criteria is met. The acquisition function can take several forms, but generally searches the region where the most improvement of the surrogate model is expected. This algorithm is particularly well suited for these experiments as it can optimize functions with noisy outputs. Furthermore, it can easily be expanded to include more optimization parameters. A more complete explanation of the full algorithm can be found in Ref. 29. Several Bayesian optimization packages are available for open source and commercial platforms.

IV. Experimental Setup

A. ECR Thruster

The thruster used in this experiment, shown firing in Fig. 2, is based on the ECR thruster designed at ONERA[2]. This thruster utilizes a coaxial design in which microwave power is injected from the back of the thruster between an inner antenna and an outer conductor which serves as both a waveguide and as the walls of the plasma source. A DC block is placed between the input coaxial cable and the thruster allowing the thruster body to float with respect to the chamber. The magnetic field is generated by permanent NdFeB magnets with a peak magnetic field of 1100 gauss inside the thruster. For the design used in this paper, gas is injected radially into the discharge region, however both axial and radial gas injection schemes have been utilized in other experiments with varying levels of success[30].



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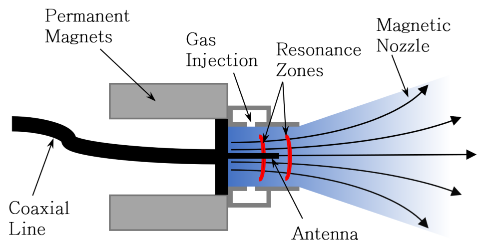


(b)

Fig. 2 (a) ECR thruster firing on 2 SCCM xenon at 20 watts input power, (b) Schematic of the thruster showing the ECR resonance zones created by two-frequency heating

B. Vacuum Facility

Initial experiments were performed in a 0.9 meter diameter by 0.9 meter vacuum chamber at PEPL, shown in Fig. 4. This chamber is equipped with a cryogenic pump capable of approximately 1,300 L/s pumping speed on xenon. Because high background pressure has been previously shown to inhibit the performance of these devices, the experiment was moved to the Junior vacuum facility, a 1 meter diameter by 3 meter chamber equipped with both turbomolecular and cryogenic pumps capable of a combined pumping speed of roughly 32,000 L/s on xenon.

C. Microwave Power and Diagnostics

We present an overview of the microwave power setup including signal sources and diagnostics in Fig. 3. Microwave power is first generated by two Mini-Circuits voltage controlled oscillators with output frequency ranges from 1,300 to 2,700 MHz. These signals are then combined using a Mini-Circuits ZX10-2-252-S+ combiner and amplified using a Comtech PST linear amplifier. The power is sampled using a Mini-Circuits ZABDC20-252H-N+ directional coupler, and the forward power is fed through a 3-dB splitter after which one output is connected to a Mini-Circuits PWR-6RMS-RC true RMS power sensor and the other is fed to a HP 8563E spectrum analyzer. The reverse port of the directional coupler is connected to a Mini-Circuits PWR-6GHZ power sensor to measure reflected power.

For the purpose of this experiment, efficiency is measured with respect to the forward power input to the thruster. The reflected power, therefore, is not taken into account, and efficiency could hypothetically be increased through the use of a matching network. It is worth noting that mixed signals, such as those generated by two-frequency heating, cannot be measured by standard Continuous Wave (CW) power sensors. Instead "True Power" sensors are required, and even with these devices, measurement bandwidth must be carefully taken into account.

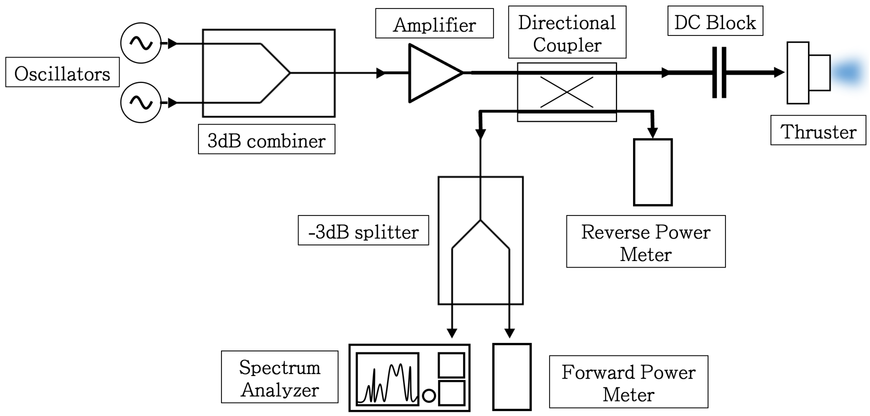


Fig. 3 Schematic showing the microwave signal generation and diagnostic components

D. Thrust Stand

The thrust stand used in these experiments, shown in Fig. 4, employs a hanging pendulum design. For our implementation, we use a counterweight on top of the pivots to increase the displacement caused by the thruster. This design is similar to that used in Ref. 3. We measure thruster displacement with a Philtec DMS-63 fiber-optic displacement sensor giving a ~ 10 nm resolution. For the initial tests, we do not employ active control to null the thruster displacement, however, this feature may be added to future tests. The thrust stand is calibrated by placing a series of ~ 0.5 gram weights at a known moment arm with respect to the pendulum pivots. A typical calibration curve is shown in Fig. 5(a).

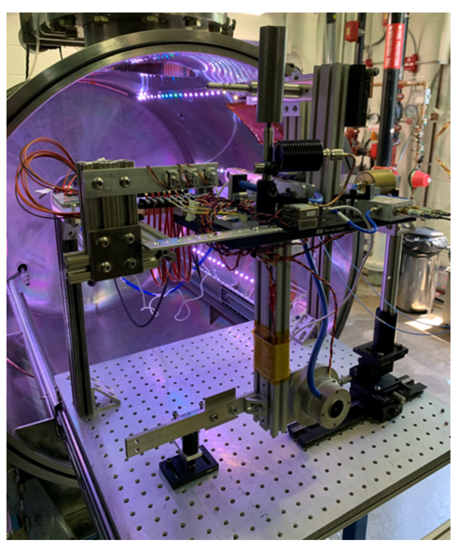


Fig. 4 Thrust stand with the ECR thruster mounted

Initial tests were performed at a 20 watt, 2 SCCM-Xe operating condition. We show a raw data trace from this test in Fig. 5 (b). Using the calibration data in Fig. 5 (a), the measured thrust was 535 giving a thrust efficiency of 3.4%. However, these tests were performed at a relatively high background pressure (over 30μTorr), which is known to cause a decrease in thruster performance. Furthermore, these tests were conducted prior to adding several features to the thrust stand to improve the accuracy of measurements taken with microwave powered thrusters, as discussed below. The measurements taken during this initial test, therefore, may not be reflective of true thrust numbers.

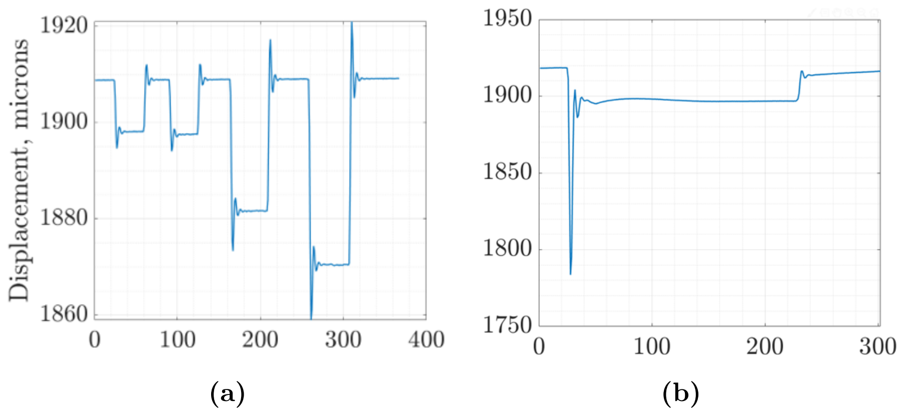


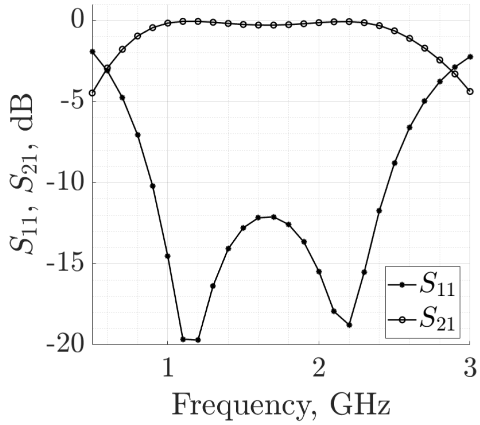
Fig. 5 (a) Typical thruster calibration curve showing displacement as successive ~ 0.5 gram weights are added, and (b) displacement as the thruster is turned on and off at a 20 watt, 2 SCCM operation condition

Thrust produced by RF and microwave powered thrusters can be particularly difficult to measure due both thermal deformation and RF/microwave interference issues. Delivering microwave power to the thruster requires the use of relatively stiff coaxial cables that both limit the sensitivity of the thrust stand and expand during operation causing false readings. Initial tests of the ECR thruster using RG-400 coaxial cable showed that cable heating could cause thrust readings on the order of those produced by the thruster itself. Although no microwave interference issues were encountered during initial tests, the thruster's proximity to sensitive electronics makes it vital to consistently check for false readings. The thrust stand therefore features several additions to make it suitable for testing low-power ECR thrusters. These include wireless power coupling, a microwave power diverter, and PID temperature control of the thruster and thrust stand.

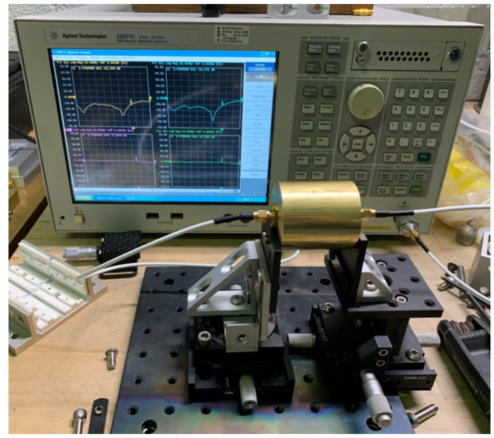
1. Wireless Power Coupler

In order to avoid false readings associated with cable heating, power is coupled to the thruster wirelessly through a custom designed wireless power coupler shown in Fig. 6 (b). These types of wireless power coupler are becoming standard practice microwave thruster measurements[30,31]. However, because of the large bandwidth required for our two-frequency ECR tests, a new coupler design was needed.

For our design, we employ a coaxial geometry somewhat similar to an air dielectric coaxial cable. This design enables a large bandwidth and is insensitive to small changes in the relative position of the two halves. Several iterations of the design were simulated in COMSOL Mulitphysics, with a final design achieving a -1 dB bandwidth from 800 to 2,500 MHz, as shown in Fig. 6(a). The design was constructed using brass as the inner and outer conductor, and the resulting scattering parameters were measured to be similar to the simulations. During initial thruster tests, we were able to operate the thruster over the full bandwidth at powers up to 50 W.



(a)



(b)

Fig. 6 (a) Simulated S parameters of the microwave wireless power coupler and (b) the final design undergoing testing with the network analyzer

2. Power Diverter

Because false readings due to microwave interference and thermal expansion are often difficult to identify, we have added a microwave power diverter to the thrust stand as an additional sanity check. For our design, a JFW RF switch is used to route incoming microwave power to either the thruster or a 50Ω dummy load. By comparing the thrust measured with power sourced to the dummy load to that measured with no power input to the thrust stand, we can quickly determine if the input microwave signal is causing false thrust readings.

3. PID Temperature Control

Finally, in order to provide stable thermal environment, thrust stand and thruster are held at constant temperatures using PID control. We implement this feature using Kapton heating strips attached to both the thruster and thrust stand. The temperature at these points is read using two DSB1820 digital temperature sensors, and heater current is controlled using an on-board micro-controller.

V. Experiment Operation and Initial Results

The optimization experiment is implemented as a LabView VI. This VI controls the microwave signal sources, diagnostics, and displacement sensor, and is coupled with a MatLab Bayesian Optimization code to select new test parameters. The initial experiment is shown in operation in Fig. 7.

Initial tests revealed several challenges associated with this type of optimization experiment. The most obvious of these difficulties was the discovery of hysteresis in thruster performance i.e. thrust varied significantly depending on whether the test point was approached from a higher or lower power state. This is a well known phenomenon in ECR plasmas, but is not typically encountered in EP thrusters[32]. Furthermore, conflicting data between power sensors revealed the need for "True Power" sensors, as mentioned above. While the power measurement issue could be solved by using new equipment, the hysteresis problem required new testing methods. An overview of the new trial point designed to eliminate the observed hysteresis technique is shown in Fig. 8. Here, the thruster is first operated at a known low-power ($\sim$ 5 watt) condition. It is then quickly switched to a higher

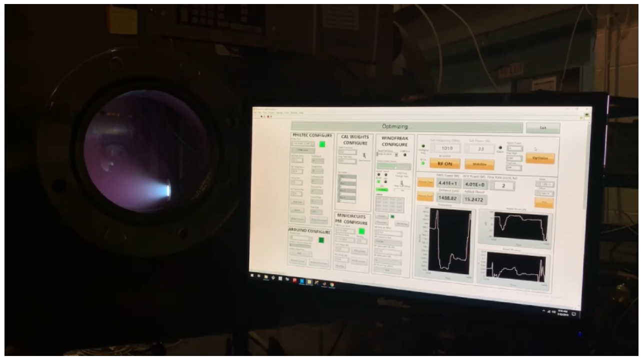


Fig. 7 Initial optimization experiment during operation. The thruster can be seen firing on the left while the LabView VI controlling the experiment is shown on the right

power ($\sim$ 30 watt) operating point, and then slowly transitioned down to the new test point using variable attenuators. Once steady state is reached at the trial point, which was found to take around 10 seconds, the thruster is quickly transitioned to the low-power operating point, and thrust is determined using the change in thrust. Finally, a new trial point is calculated by the optimizer and the process repeats.

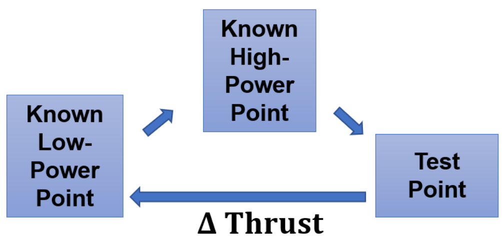


Fig. 8 Diagram showing the routine used to measure thrust at each new test point. Relative thrust is measured by taking the Δ Thrust between the test point and the known low-power set point.

VI. Conclusions

In this paper, we have presented the preparations for an upcoming optimization experiment using two-frequency heating to improve the performance of a low-power ECR magnetic nozzle thruster. We show that ECR thrusters are well suited for optimization using custom input waveforms, and present our choice of optimization variables: f_1, f_2 and P_1/P_1. The thrust measurement techniques and experiment facilities were presented, including a newly developed thrust stand. Finally, we present a new technique for quickly iterating through trial points while avoiding the effects of hysteresis. The full results of the tests implementing these new techniques will be the subject of future publications.

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