

SINGLE AND MULTI-PULSE LOW-ENERGY CONICAL THETA PINCH INDUCTIVE PULSED PLASMA THRUSTER PERFORMANCE

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ABSTRACT

Impulse bits produced by conical theta-pinch inductive pulsed plasma thrusters possessing cone angles of 20°, 38°, and 60°, were quantified for 500J/pulse operation by direct measurement using a hanging-pendulum thrust stand. All three cone angles were tested in single-pulse mode, with the 38° model producing the highest impulse bits at roughly 1 mN-s operating on both argon and xenon propellants. A capacitor charging system, assembled to support repetitively-pulsed thruster operation, permitted testing of the 38° thruster at a repetition-rate of 5 Hz at power levels of 0.9, 1.6, and 2.5 kW. The average thrust measured during multiple-pulse operation exceeded the value obtained when the single-pulse impulse bit is multiplied by the repetition rate.

INTRODUCTION

The IPPT is an electrodeless space propulsion device where a capacitor is charged to an initial voltage and then discharged producing a high current pulse through a coil. The field produced by this pulse ionizes propellant, inductively driving current in a plasma located near the face of the coil. Once the plasma is formed it can be accelerated and expelled at a high exhaust velocity by the electromagnetic Lorentz body force arising from the interaction of the induced plasma current and the magnetic field produced by the current in the coil.

Thrusters of this type possess many demonstrated and potential benefits that make them worthy of continued investigation. The electrodeless nature of these thrusters eliminates the lifetime and contamination issues associated with electrode erosion in conventional electric thrusters. Also, a wider variety of propellants are accessible when compatibility with metallic electrodes is no longer an issue. IPPTs have been successfully operated using propellants like ammonia, hydrazine, and CO₂, and there is no fundamental reason why they would not operate on other in situ propellants like H₂O. It is well-known that pulsed accelerators can maintain constant specific impulse (I_{sp}) and thrust efficiency (η_t) over a wide range of input power levels by adjusting the pulse rate to hold the discharge energy per pulse constant. It has also been demonstrated that an inductive pulsed plasma thruster can operate in a regime where η_t is relatively constant over a wide range of I_{sp} values (3000-8000 s). Finally, thrusters in this class have operated in single-pulse mode at high energy per pulse, and by increasing the pulse rate they offer the potential to process very high levels of power using a single thruster.

There has been significant previous research on IPPTs designed around a planar-coil (flat-plate) geometry [1]. The most notable of these was the Pulsed Inductive Thruster (PIT) [2]. During the early investigations on the PIT geometry [3], testing with smaller-scale planar-coil thrusters revealed differences in propellant utilization efficiency between the cases where propellant was injected using a pulsed gas system and where the coil was located in an ambient backfill environment with no pulsed gas injection employed. In these experiments, the latter

cases outperformed the former. It was believed based upon current density measurements that the non-uniform propellant distribution in the pulsed gas injection cases resulted in poorer overall coupling to between the coil and the plasma. In more recent low-energy (<100 J/pulse) experiments an ambient backfill environment was employed and a separate preionization source was used to generate a seed-plasma before the application of the current pulse through the coil. In these tests, a plasma sheet was only produced by the current pulse through the coil when a sufficiently strong magnetic field was applied to divert the preionized plasma from the natural diffusion path along the centerline to a path over the coil face [4,5].

An approach that could potentially result in a uniform propellant density over the face of the inductive coil that was also easier to preionize was to alter the coil geometry such that it more closely aligns with the natural path followed by the injected propellant. This strategy was the motivation for the experimental work on the conical theta-pinch (CTP) IPPT geometry detailed in this paper. Several CTP IPPTs possessing different cone angles were fabricated and operated on a thrust stand, where the impulse bit (I_{bit}) was directly measured. These devices were operated in single-pulse mode. The highest performing geometry was then tested, again on the thrust stand, in a repetition-rate mode of 5 Hz processing up to 2.5 kW of average power representing to our knowledge the highest power at which a repetitively-pulsed thruster has been operated.

The thrusters and test facility used in this study are described in the next section, and are then followed by a presentation of the data acquired in both single-pulse and repetitively-pulsed modes.

EXPERIMENTAL APPARATUS

The CTP thruster consists of a thruster coil, capacitor bank and switch, and gas injection system. Three conical theta-pinch inductive coils were constructed for performance testing (see example with labeled geometry in Fig. 1). Two of the coils have length l_{coil} of 10 cm (4 in) and a minor radius r_{coil} of 4 cm (1.6 in). The half-cone angles θ for these coils are 20° and 38° . The third coil has l_{coil} of 5 cm (2 in), r_{coil} of 4 cm (1.6 in), and θ of 60° . In all three cases the inductance of the coil is $240 (\pm 20)$ nH as measured using an Agilent 4285A precision inductance-capacitance-resistance (LCR) meter. The 38° coil in Fig. 1 is shown prior to being encased in RTV, which serves to insulate the coil surface from the ionized propellant. This insulating layer was covered with aerosol boron nitride spray to prevent ablation of the RTV surface.

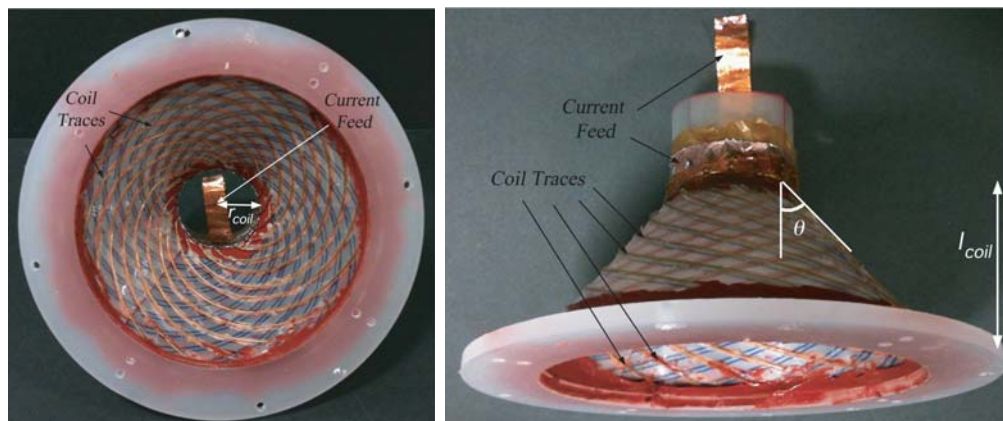


FIGURE 1: Images of the 38° conical theta pinch inductive coil showing (a) front view along the axis and (b) top view.

The conducting traces comprising each coil were assembled in two layers. In all, the coil is formed from sixteen separate Kapton-insulated 22 gauge wires. Each wire completes a half-turn spiral going from the back-end of the cone (smaller radius position) to the front and another half-turn spiral in the same azimuthal direction returning to the back-end of the cone on the other side

of the insulating sheet. The insulating sheet is comprised of two layers of 0.25 mm (0.01 in) thick Mylar that provides the physical structure for the cone. When superimposed, the current passing through the windings creates a nearly-azimuthal net current in the coil. The windings are electrically connected in parallel to common current feed and return locations at the back of the cone.

The capacitor bank consisted of four 10 μF capacitors connected in parallel. They are vacuum compatible, oil-filled metal cans with a series inductance of not more than 20 nH. The energy in the capacitor bank was discharged through a Perkin Elmer triggered spark gap switch. The capacitor bank and switch were placed inside an atmospherically-pressurized enclosure that was mounted on the thrust stand directly behind the thruster. The entire assembly is shown on the thrust stand in Fig. 2.

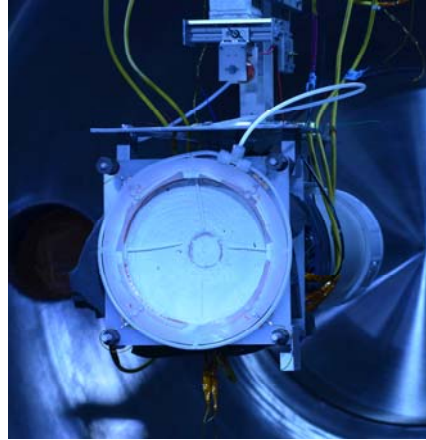


FIGURE 2: 60-deg IPPT with atmospherically-pressurized enclosure (behind coil) mounted on the thrust stand

The capacitor bank was charged using a custom CCS-series (formerly designated CCDS) high-voltage power supply from General Atomics Electronic Systems (GA-ESI). The CCS-series, with specifications given in Ref. [6], is designed for rapid, efficient, repetitive charging of capacitor banks. Each supply (of 7) in the rack has a maximum output voltage of 40 kV and is capable of delivering an average of 16 kJ/s DC power when charging to the maximum voltage. The average power throughput decreases linearly with the voltage setpoint. An electrical circuit (shown in Fig. 3) was implemented to protect the power supply as it would remain connected to the thruster (pulsed load) during the discharge during repetition-rate operating mode.

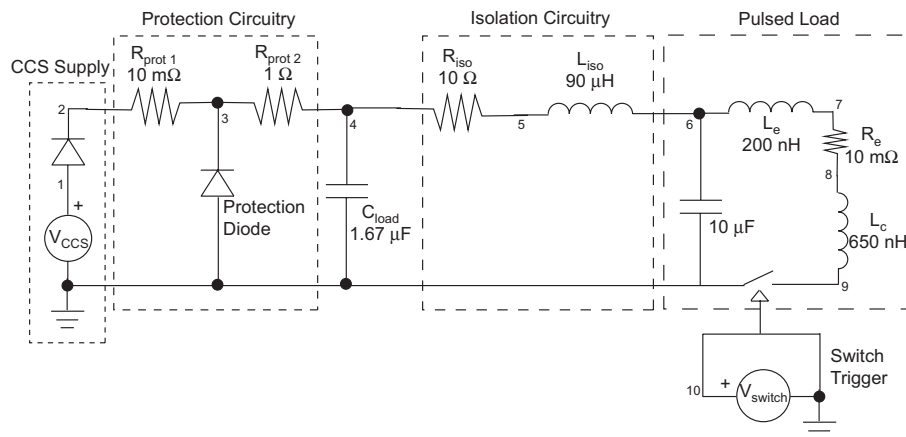


FIGURE 3: Capacitor charging system circuit schematic.

Gas flow was controlled using an MKS metal-sealed type 1479A flow controller with maximum flow rate of 10,000 sccm. Research grade argon and xenon propellants were used for all data presented in this paper. A steady-state gas flow was employed in the CTP since the

thruster was not designed to include a fast pulse valve. Four insulating tubes were connected to an upstream manifold and aligned on the surface of the cone azimuthally-equidistant from each other. Several holes were cut into the tubes at different axial locations to permit gas to flow into the thruster in the azimuthal direction.

The vacuum facility is a 7.6-m (25-ft.) long, 2.7-m (9-ft.) diameter stainless steel cylindrical vacuum chamber. The chamber can be evacuated to a base pressure (gauge calibrated on N_2) of 7.6×10^{-5} Pa (5.7×10^{-7} torr), maintained by either two 32" cold-trapped diffusion pumps with a combined unobstructed pumping speed of 65,000 l/s or two 2400 l/s turbopumps used in combination with two 9500 l/s flange-mounted GHe cryopumps (all pumping speeds on N_2). The diffusion pump cold traps are cooled using a recirculating Polycold chiller.

The hanging pendulum-type Variable Amplitude Hanging Pendulum with Extended Range (VAHPER) thrust stand [7] is used to perform thrust measurements in the present work. In general, as a thruster is operating the VAHPER stand directly measures thrust by monitoring the level of displacement of a pendulum arm from an equilibrium position. Displacement of the thrust stand arm is measured using a non-contact light-based linear gap displacement transducer (LGDT). The pendulum arm displacement that occurs when known forces are applied permits the calculation of thrust from pendulum arm displacement data acquired during thruster operation. The stand was recently modified through the addition of a pulsed-thruster calibration system [8].

RESULTS AND DISCUSSION

SINGLE-PULSE OPERATION

Time-resolved images of the CTP thruster are presented in Fig. 4. These images were obtained using a Shimadzu HPV-2 model CCD camera at a framing rate of 1 MHz, with an exposure time of 125 ns. The images are black and white, and unfiltered, representing all light from the discharge during the time specified. A current waveform, obtained for a discharge at a capacitor bank charge voltage of 4 kV, is included with the frames to provide an temporal orientation showing when these images are obtained.

The images presented show the light emitted by the plasma over the first two half-cycles of the discharge. For the record, the glow at the end of the first half cycle continues beyond that shown to $t=11 \mu s$. Also not shown is a faint glow that appears in the first few frames of the third half-cycle. The high-intensity glowing plasma initiates at the times where the coil current crosses zero, as these represent the times of greatest change in the coil current (greatest di/dt), and consequently the greatest value of the induced fields in the plasma. The light emission starts near the exit of the thruster at $t=1 \mu s$ and $t=16 \mu s$ and expands backwards towards the narrow end of the cone growing in intensity until peaking a few microseconds into the half cycle. There are visible non-uniformities in the light emission, but the emission grows to a very intense level (nearly saturating the camera) over the entire interior volume during the first half-cycle of the pulse. During the second half cycle, the glow is less intense and shorter-lived. This could be due either to the lower level of current during the second half cycle or the reduction in gas near the coil as it may have been partially accelerated away from the coil during the first half cycle.

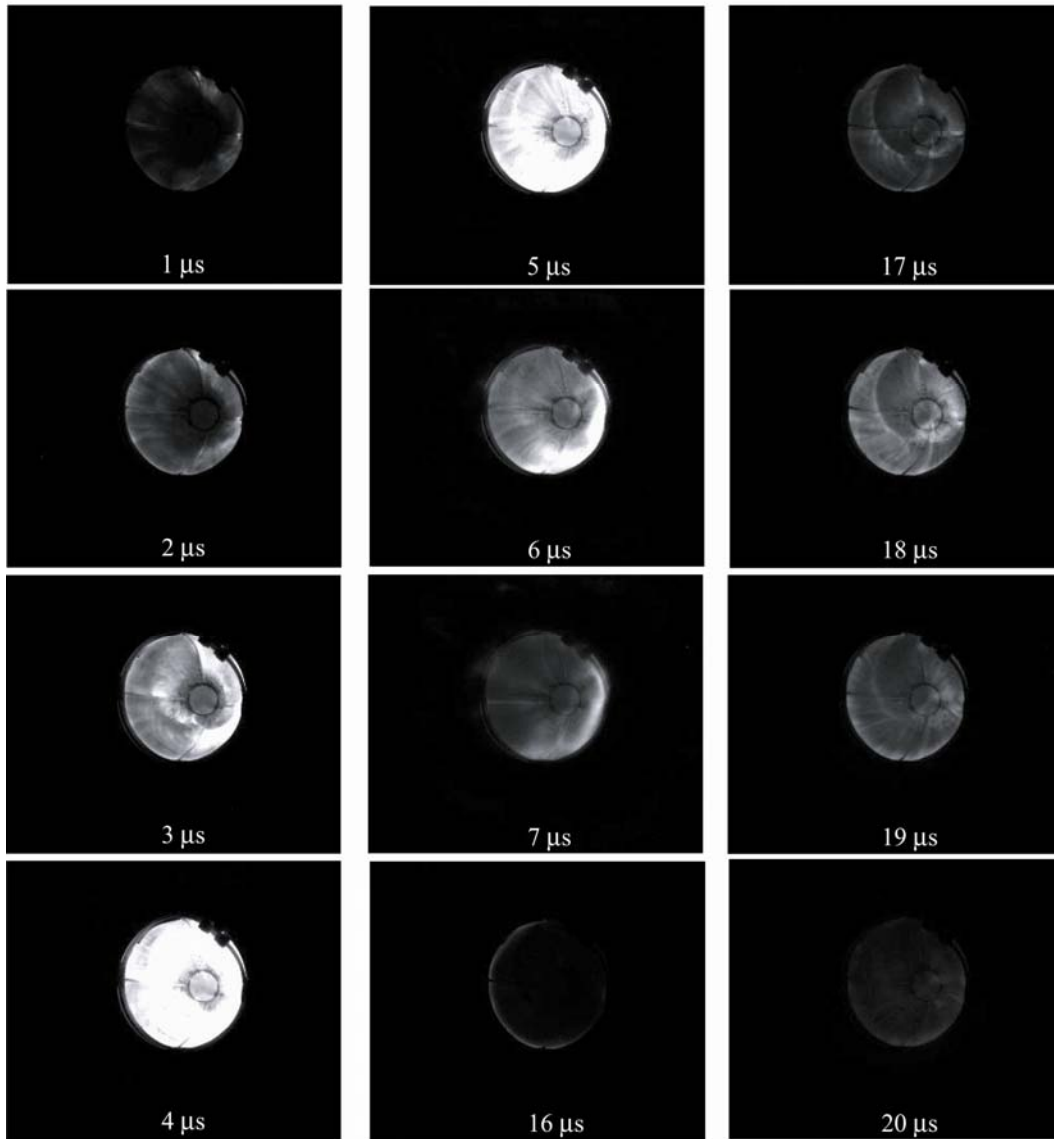
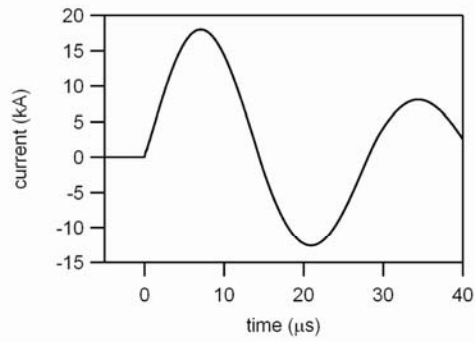


FIGURE 4: Current waveform (at 4 kV capacitor charge voltage) and time-resolved (black and white) images of the 38° CTP thruster obtained with an image gate time of 125 ns for the times indicated in the frames.

Performance measurements are presented in Fig. 5 for operation of multiple coil angle CTP thrusters. Impulse bit measurements are presented in Fig. 5a and 5b for argon and xenon, respectively. The maximum measured impulse bit was approximately 1 mN-s for both propellants, and was only produced by the thruster with a 38° half-cone angle. When the mass

flow rate was increased beyond the range for which data are presented in this report, the base pressure in the vacuum vessel increased to values at which high-voltage arcing prevented performance measurements. The impulse bit peaks faster for xenon propellant, and the performance is much improved on xenon at 20° relative to argon at the same angle. We can speculate that xenon, being a heavier gas, may remain nearer to the coil for a longer period of time. This would leave a greater mass of propellant within the volume over which electromagnetic coupling between the coil and the plasma is possible permitting better electrodynamic energy transfer [9].

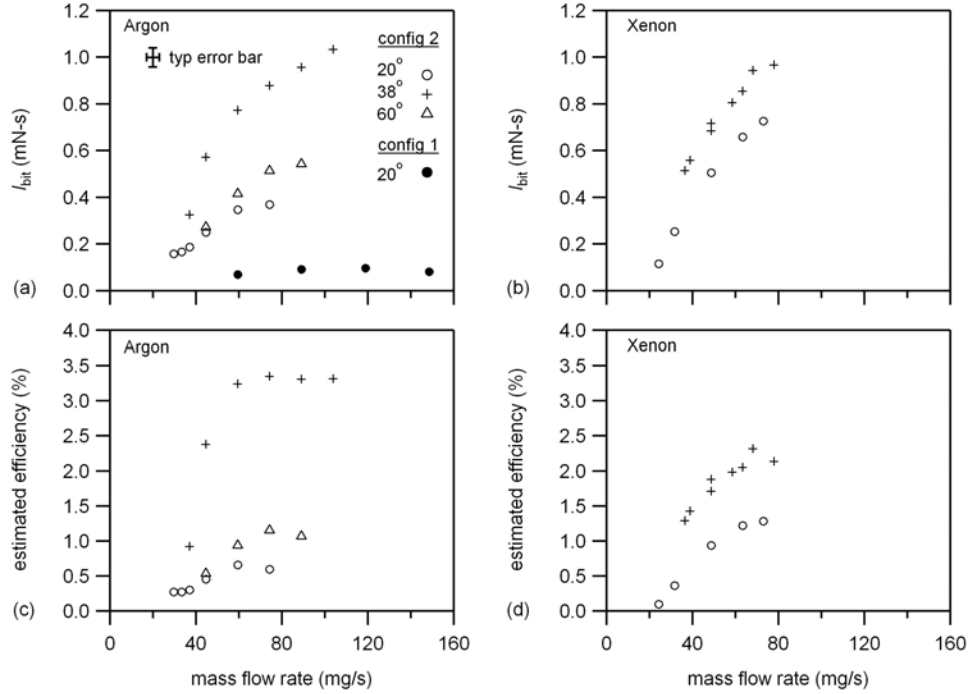


FIGURE 5: Measured impulse bit (with a typical error bar displayed) of the CTP as a function of steady-state mass flow rate for operation on (a) argon and (b) xenon. Estimated efficiency for operation on (c) argon and (d) xenon. All data obtained for single pulse operation at a charge voltage of 5 kV (500 J/pulse).

Since a steady-state propellant feed was used, we must estimate the mass bit to calculate an estimated efficiency. A characteristic length for gas injection is taken as the cone axial length l . A characteristic time for gas injection is estimated as

$$t_{char} = \frac{l}{a} \quad (2.1)$$

where a is the sound speed of the gas (at 25°C). The mass bit is then estimated as the amount of gas that would enter the thruster in this characteristic time

$$m_{bit} = t_{char} \dot{m} \quad (2.2)$$

where \dot{m} is the mass flow rate. This assumption is consistent with operation with a pulsed gas valve that only permitted gas to flow into the thruster over the length of time t_{char} . The efficiency is obtained using the measured impulse bit I_{bit} , initial charge voltage V_0 , bank capacitance C , and the estimated mass bit:

$$\eta = \frac{I_{bit}^2}{m_{bit} C V_0^2} \quad (2.3)$$

The estimated efficiency for operation argon and xenon propellants is given in Fig. 5c and 5d. We observe that when estimated in this manner, the efficiency is only a few percent. Interestingly, the efficiency on xenon at a cone angle of 20° is greater than that on argon at the same angle, but these trends are reversed at 38° .

It should be noted that low power planar (flat-plate) pulsed inductive thrusters were highly lossy, producing incompletely-formed current sheets (magnetically permeable with comparable magnetic convection and diffusion timescales) with a high degree of spatial variability. They were also tested in a 'static' gas fill configuration, and much of the inductive work was expended in entrainment of the gas, which is a highly inelastic process leading to low inherent efficiencies. For example, the 20-cm flat-plate thruster only had an efficiency of a few percent in the static fill case [1]. We expected similar gas profiles and entrainment losses in the CTP thruster employing continuous gas injection, so the low efficiency results are unsurprising. By way of comparison, the PIT MkI and MkV, which were far better optimized in an electrodynamic sense and had pulsed propellant injection, only yielded efficiencies in the range of 15-30% on argon.

The force vector in pulsed inductive thrusters is generally directed perpendicular to the coil. Unlike the planar pulsed inductive thrusters, the force vector applied to the plasma in the CTP thruster has a significant component in the radial direction, which, excluding any energy recovery mechanisms, does not contribute to the impulse bit. This might lead to the conclusion that the greater angle should perform better, but this is not shown in the impulse bit data where the 38° cone performed best. In the present CTP thruster testing, the acceleration picture is complicated by the energy expended on gas entrainment, the potential containment of gas provided by the smaller angle cones, and the stray inductance remaining in the system. The data presented herein are not sufficient to deconvolve the acceleration picture beyond what has been speculated in the preceding discussion.

REPETITION-RATE OPERATION

A voltage trace of the capacitor bank voltage during a repetition-rated test of the thruster is shown in Fig. 6a. The charge system performed as desired, re-charging the thruster capacitor bank rapidly after every discharge. A waveform from a test with the 38° conical theta-pinch IPPT is displayed in Fig. 6b for operation at 5 Hz for 5 seconds. During pulsed operation the thrust stand oscillates about a displaced position, with the difference between the displaced neutral (average) position and zero corresponding to the average thrust imparted by the thruster [8].

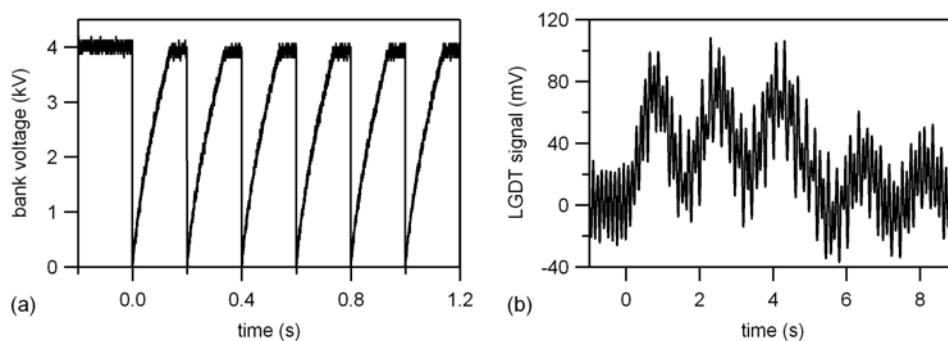


FIGURE 6: (a) Voltage waveform and (b) LGDT signal from a 5 Hz, 5 second repetition-rated test of the 38° conical theta-pinch IPPT.

The average thrust as a function of mass flow rate for 5 Hz operation of the 38° conical theta-pinch IPPT is presented in Fig. 7 for three separate capacitor charge voltages. During repetition-rate testing there were issues with the high-voltage insulation on the charge and pulse lines short-circuiting a 5 kV. The trend in these data, specifically the 4 kV charge data, show an increasing level of thrust as a function of mass flow rate, mirroring the single-pulse data presented in Fig. 2.14 for single-pulse operation. We compare the single 5 kV data point in Fig. 7 with the corresponding data point in Fig. 5, observing that the average thrust operating in repetition rate

mode is greater than simply calculating 5 times the single shot impulse bit. This suggests better gas acceleration in the pulsed mode, but the exact mechanism for this improvement remains an open question for future study.

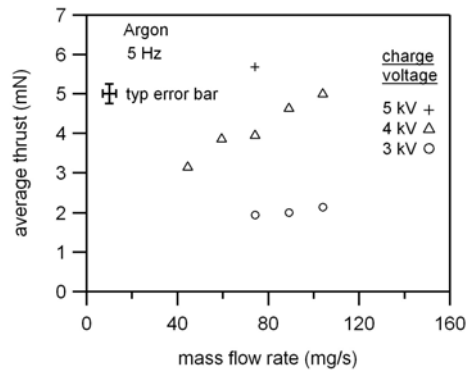


FIGURE 7: Average thrust as a function of continuous mass flow rate for a 5 Hz, 5 second repetition-rated test of the 38° conical theta-pinch IPPT operating on argon.

Operation at 5 Hz and charge voltages of 3, 4, and 5 kV represents average powers of 0.9, 1.6, and 2.5 kW. By way of comparison, to our knowledge the previous highest power pulsed thruster operated in a repetition-rate mode was the pulsed plasma thruster on the Earth Observer 1 spacecraft, which operated in ground testing at 56-70 W (at a pulse frequency of 1 Hz), and was estimated to have 12.6 W (also at 1 Hz) available during the mission for in-space repetitive-pulse operation [10]. The CTP IPPT tested exceeds the ground test repetition-rate power throughput by more than an order of magnitude.

SUMMARY AND CONCLUSIONS

The following summary and conclusions arise from this work:

- Conical theta pinch IPPTs with cone angles of 20°, 38°, and 60° were fabricated, mounted on a thrust stand, and operated in a single-pulse mode in a large vacuum chamber. While using continuous gas flow, direct measurements of the impulse bit were acquired.
- The single pulse performance of the thruster peaks for the 38° conical theta pinch, with an impulse bit of about 1 mN-s for both argon and xenon propellants.
- The estimated efficiencies are low (all under 5%) but not unexpected based upon historical data from lower energy-per-pulse inductive thrusters and the direction of the force vector in a conical theta-pinch thruster.
- A capacitor charging system was assembled to provide for fast recharging of an IPPT capacitor bank, permitting repetition rate operation.
- A conical theta-pinch IPPT was tested at repetition rate of 5 Hz, which at 5 kV on a 40 μF bank represents a power of 2.5 kW. To our knowledge this is over an order of magnitude greater than any previous repetition-rate operated pulsed plasma thruster.
- The average thrust measured during repetition-rate operation was greater than simply multiplying the repetition rate and the single-pulse impulse bit measurement.

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