Single and Multi-Pulse Low-Energy Conical Theta Pinch Inductive Pulsed Plasma Thruster Performance

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Inductive Pulsed Plasma Thrusters

- Energy stored in capacitor banks
- High current switch permit discharge through an inductive coil
- Fast-rising current ionizes/electromagnetically accelerates gas

- Demonstrated and potential benefits
  - Electrodeless
  - Potential to use a wide variety of propellants (Ammonia, CO₂, H₂O, etc.)
  - Constant $I_{sp}$ and thrust efficiency over a wide range of power
  - Regime of relative constant efficiency over a range of $I_{sp}$
  - Potential to process high power in single thruster (high rep rate)
Conical Theta-Pinch (CTP) IPPT

- Propellant potentially more contained and uniform on coil surface
- Three coils fabricated ($\theta=20^\circ$, $38^\circ$, $60^\circ$) (~240 nH)
- Capacitors located directly behind coil (in pressurized enclosure)
- Spark gap-switched capacitor bank
- Direct thrust stand impulse bit measurement

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$r_{\text{coil}}$</th>
<th>$I_{\text{coil}}$</th>
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<tbody>
<tr>
<td>$20^\circ$</td>
<td>4 cm</td>
<td>10 cm</td>
</tr>
<tr>
<td>$38^\circ$</td>
<td>4 cm</td>
<td>10 cm</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>4 cm</td>
<td>5 cm</td>
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Capacitor Charging System

- 40 µF capacitor bank
- 16 kJ/s / 40 kV capacitor charging supply (approximate linear power derating with charge voltage)
- Capacitor bank connected to power supply during pulse – necessitates isolation and protection circuitry
- Pushes repetition-rate limit to ability to rapidly trigger spark-gap switch
High-Speed Imaging

- All light (B&W), 125 ns exposures
- Glow begins at front of thruster and grows backwards at start of 1st/2nd half-cycles
- High intensity over coil in first half-cycle; lower in second half-cycle
- Visible non-uniformities
- Lower coil current / lower level of gas(?) in 2nd half-cycle
Single-Pulse Performance

- Max $I_{bit}$ of $\sim 1$ mN-s
- Max $I_{bit}$ with $\theta=38^\circ$
- Impulse bit peak faster for xenon
  - propellant utilization/more mass near coil?
- High-voltage stand-off issues prevent measurements above flow rates shown
Single-Pulse Performance

- Steady-state mass flow necessitates estimating efficiency

\[ t_{\text{char}} = \frac{l}{a} \quad m_{\text{bit}} = t_{\text{char}} \dot{m} \quad \eta = \frac{I_{\text{bit}}^2}{m_{\text{bit}} C V_0^2} \]

- Efficiency on argon higher, but both are low
  - Force vector in CTP partially in wrong direction for thrust
  - Similar to peak values in 20-cm PIT (static-fill in late 1960s)
    - Profile/entrainment losses high w/out pulsed injection
  - PIT MkI / MkV (on argon) efficiencies only 15-30% at high energy per pulse
Repetitive Charging and Pulsing

- Repetition rate operation at 5 Hz (up to 2.5 kW average power)
- Repetition rate limit was trigger module for spark gap switch
- Pulsing over 5 seconds
- Thrust stand average displacement yields average thrust during operation
Repetition-Rate Performance

• Average power of 0.9, 1.6, and 2.5 kW (all at 5 Hz)
• 5 kV data in repetition-rate mode greater than 5x the impulse bit in single pulse mode
• To our knowledge, the highest power repetitively-pulsed (i.e. non-CW) discharge
  • Comparison w/ EO-1 PPT (56-70 W @ 1 Hz in ground testing, 12.6 W @ 1 Hz for in-space pulsing)
Conclusions

• Fabricated and tested CTP IPPTs at cone angles of 20°, 38°, and 60°, and performed direct single-pulse impulse bit measurements with continuous gas flow

• Single pulse performance highest for 38° angle with impulse bit of ~1 mN-s for both argon and xenon

• Estimated efficiencies low, but not unexpectedly so based on historical data trends and the direction of the force vector in the CTP

• Capacitor charging system assembled to provide rapid recharging of capacitor bank, permitting repetition-rate operation

• IPPT operated at repetition-rate of 5 Hz, at maximum average power of 2.5 kW, representing to our knowledge the highest average power for a repetitively-pulsed thruster

• Average thrust in repetition-rate mode (at 5 kV, 75 sccm argon) was greater than simply multiplying the single-pulse impulse bit and the repetition rate
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