Design and Testing of a Small Inductive Pulsed Plasma Thruster

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Introduction

• The Inductive Pulsed Plasma Thruster (IPPT) is an electromagnetic thruster that impulsively accelerates ionized propellant via the $\mathbf{J} \times \mathbf{B}$ body force.

• Potential advantages include:
  • Long operational life-time due to the absence of high-current electrodes
  • Ability to run on readily storable molecular propellants such as ammonia
  • $I_{SP}$ can be independent of jet-power, $P_{Jet}$

• A small solid-state switched IPPT (1-5 kWe) was built with the goals of:
  • Demonstrating operation of an integrated solid-state switched IPPT.
  • Building a device that can be tested in cyclic mode on a thrust-stand.
  • Serve as a test-bed for solid state switching circuitry and pulsed gas valves.
  • The modular design of the device allows for a variety of configurations to be tested.
Design: Acceleration Coil

• The coil is wound on a Lexan coil form, and has six two-turn leads in parallel, clocked around the form at 60° intervals. Each turn is in the shape of an Archimedes-spiral ($r = a + b\theta$). The leads are No. 10 magnet wire, laid in CNC-machined grooves in a Lexan coil-form. Each lead is also insulated with Teflon heat-shrink tubing.

• Coil Dimensions:
  • o.d. = 270 mm
  • i.d. = 100 mm

• The coil is potted with Momentive RTV-560 high-voltage silicone insulation compound for additional insulation.

• The coil face was covered with an annular alumina-coated Mylar disk which provides insulation between the plasma and the coil and serves as a refractory plasma-facing wall.

Partially assembled device with acceleration coil, capacitor bank, and switch assembly.
Design: Circuit and Switch Assembly

- Inductance: discussed later
- Capacitance: 9.88 $\mu$F
- Switch: Dynex PT85QWx45 pulse-power thyristor, 4.5 kV max. hold-off voltage, 30 kA surge current, max. $dl/dt$ of 22 kA/$\mu$s
- Diode: Dynex DSF21545SV fast recovery diode, 20 kA max. current, 7 $\mu$s recovery time, 1.8 mC reverse recovery charge
- Thyristor and Diode are held in a clamp assembly and compressed with a force of 40 kN.
Design: Gas Valve and Pre-ionizer

- Pulsed Gas-Valve: a modified solenoid fluid control valve
  - opening time of 300 μs.
  - 25-100 μg of propellant / pulse (in multi-pulse operation)
- Glow-discharge Pre-ionizer uses a 0.3 μF capacitor charged to ~ 4 kV
Bench-top Testing: Determination of Circuit Inductance

- Total circuit inductance was measured with the diode removed (ringing discharge)
- Coil inductance was calculated with QuickField v5.6
- Results from both were fit with the following function:

\[ L(z) = L_\infty \left(1 - k_0^2 e^{-2(z/z_S)}\right) \]

<table>
<thead>
<tr>
<th>Fitting Parameter</th>
<th>Quantity fit to:</th>
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<tbody>
<tr>
<td>( L_\infty ) (nH)</td>
<td>( L_{\text{eff}} ) ( 705 \pm 3 ) ( 1,041 \pm 7 )</td>
</tr>
<tr>
<td>( z_S ) (mm)</td>
<td>( L_{\text{circ}} ) ( 57 \pm 1 ) ( 57 \pm 3 )</td>
</tr>
<tr>
<td>( k_0 )</td>
<td>( 0.92 \pm 0.01 ) ( \text{NA} )</td>
</tr>
<tr>
<td>( x^2 / n )</td>
<td>( 0.4 ) ( 0.1 )</td>
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- Calculated Coil Inductance: 705 nH
- Inferred External Inductance: 336 nH
Bench-top Testing: Component Testing at High Voltage

- Acceleration coil circuit tested up to 3 kV.
- Fast recovery diode failed at about 2 kV. at \( V_{ch} \sim 1.8 \text{ kV} \), \( \Delta Q = 4 \text{ mC} > Q_{rr} = 1.8 \text{ mC} \)
- Circuit Resistance decreases as \( V_{ch} \) increases.
Vacuum Testing: Pre-ionizer

- Pre-ionizer capacitor with $C = 0.3 \, \mu F$ charged to $4.1 \, kV$: $E_{PI} = 2.5 \, J$

- Breakdown of the gas (argon) occurred when the valve is opened, allowing gas to bridge the electrodes

- The PI worked at cyclic rates of 1 Hz – higher rates are possible.

View of the thruster in the vacuum chamber

Pre-ionizer discharge
Vacuum Testing: Complete System

- Single-shot operation at $V_{Ch} = 2$ kV, with and without PI, Peak $I_{Coil} = 4.05$ kA
- A plasma formed even without the PI, i.e. just due to the $dI/dt$ of the acceleration coil circuit itself
- The plasma formed with the PI appears to be brighter
- Repetitive operation demonstrated at cyclic-rate of 2 Hz
- A clog in the valve inlet was determined to have prevented operation at higher cyclic rates
- Insulation failures noticed after gas re-circulation in the chamber caused shorting.

View of the thruster in the vacuum chamber

The IPPT thruster in operation
Conclusions and Future Work

- Cyclic operation of the IPPT has been demonstrated with all sub-systems functioning.
- Modifications are being made prior to next phase of testing:
  - Thyristor electrodes and terminations have been re-designed
  - HV insulation being re-done
  - Valve to be cleaned and rebuilt
- Subsequently, thruster to be installed in a larger chamber and thrust measurements made.
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