High Pulse Rate Inductive Pulsed Plasma Thrusters

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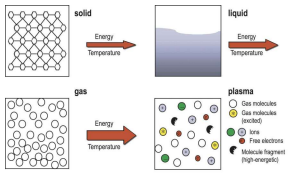
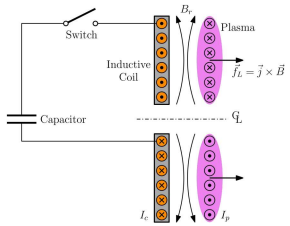
Plasma Crash Course for the Uninitiated

- Plasma is the 4th state of matter
- Quasi-neutral group of charged particles which exhibit "collective behavior"
- Responds to electric and magnetic fields



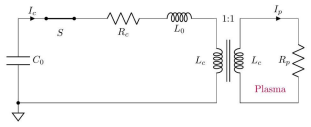
Inductive Pulsed Plasma Thrusters (IPPTs)

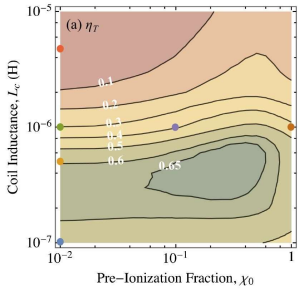
- Type of electric propulsion (EP) that uses induced electric and magnetic fields to form and accelerate plasma
- So-called $\vec{j} \times \vec{B}$ force
- Slow pulse rates ($f_p \leq 100$Hz) → pulsed gas injection
- Fast pulse rates ($f_p \geq 1$kHz) → steady gas injection
- Higher f_p → lower per-pulse discharge energy (for given power)

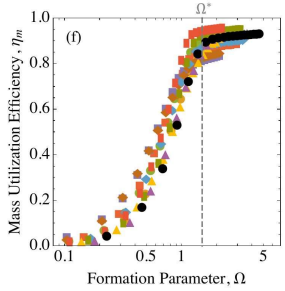


IPPT Theory and Modeling

- *RLC* circuit model coupled to plasma model [1]
- Effects of pre-ionization on formation indicated optimal range of parameters [2]
- Formation parameter and scaling law derived and critical value identified [2]

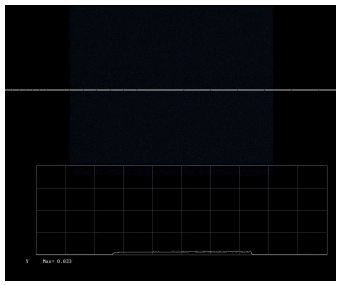


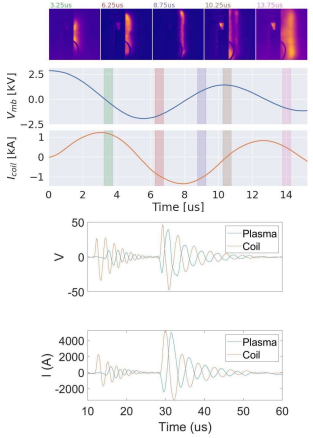




Current Sheet Formation at Low Discharge Energies

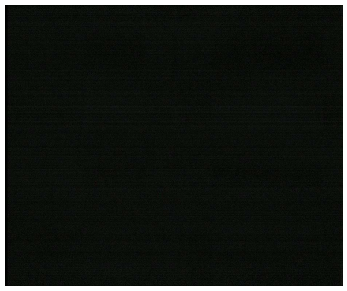
- Current sheet: a thin layer of plasma which contains most of the induced current
- Compact (OD = 6in) IPPT designed to investigate current sheet formation at ≤10J energies
- High speed imaging shows formation of structure visually consistent with current sheet
- Rogowski probe shows presence of significant azimuthal current in plasma
- Axial B-dot measurements suggest sheet is permeable to magnetic fields

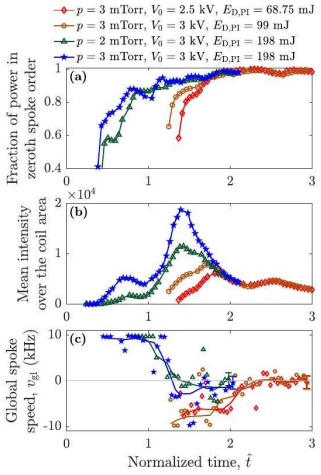




Rotating Spokes and Self-Organization

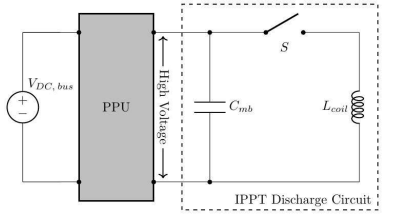
- High speed imaging revealed the onset of spokes during current sheet formation
- Spoke mode order ~ 18, inverse energy cascade to lower orders
- Spoke rotation mostly in $\vec{E} \times \vec{B}$ direction but at speed ≈ critical ionization velocity
- Sheet formation and ejection occur on half cycle basis



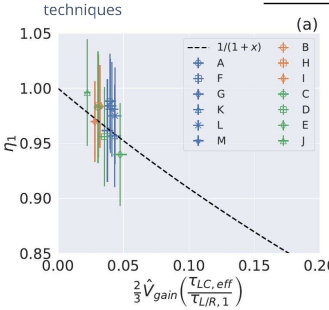


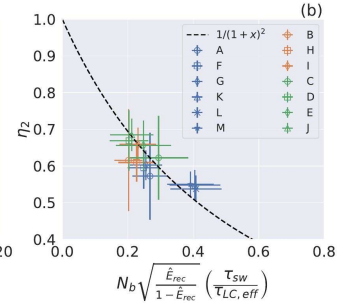
Power Processing Unit for Supporting High Pulse Rate IPPTs

- Power processing unit (PPU) needed to support high pulse rate IPPT operation
- Allows inductive recapture
- Theoretical and SPICE models developed
- Notable performance:
  - Pulse rates: 1 – 10kHz
  - Power: 1 – 10kW
  - Voltage gain: 14.4 – 25.5
  - Output voltage: 2 – 3kV
  - Efficiency: 54 – 70%
- Energy partitioning using SPICE model reveals significant switching losses
- Possibly alleviated by using so-called "soft-switching" techniques



Case	$E_{R,1}$	$E_{R,2}$	E_{sw}	$E_{misc.}$	E_{loss}	E_{rch}
	[mJ]					
G	79	128	529	24	760	1184
I	49	92	442	26	609	1185
J	36	84	380	21	521	1148





3 key timescales:
- τ_{LC}: effective energy transfer
- $\tau_{L/R}$: energy dissipation timescale
- τ_{sw}: switching timescale

Scaling laws indicate upper limit on the supported pulse rate:

$$f_p \lesssim \frac{\gamma}{N_b\sqrt{\hat{E}_{rec}}\hat{V}_{gain}\tau_{sw}}$$

Future Work, References, and Acknowledgments

Future Work:

- Continued experiments to investigate current sheet formation at low pulse rates

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Graduate Students: Curtis Promislow, Arvindh Sharma, Cameron Marsh, and Gordon McCulloh

References:

[1] K. Polzin, A. Martin, J. Little, C. Promislow, B. Jorns, and J. Woods, "State-of-the-art and advancement paths for inductive pulsed plasma thrusters," Aerospace, vol. 7, no. 8, p. 105, 2020.
[2] J. Little, G. McCulloh, and C. Marsh, "Ionization and current sheet formation in inductive pulsed plasma thrusters", Physical Review E, Submitted for Publication

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