Inductive Plasma Thruster (IPT) for an Atmosphere-Breathing Electric Propulsion System: Design and Set in Operation


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Atmosphere-Breathing Electric Propulsion (ABEP)

- Orbiting at VLEO, use of residual atmosphere as propellant;
- Intake collects the atmosphere molecules (mostly N$_2$ and atomic O);
- Thruster ionizes and accelerates for drag compensation (not only).

Inductive Plasma Thruster (IPT) → We started with IPG6-S

- 3.3 MHz, 5.5 turns coil, N₂, O₂, Ar, < 4 kW in operation;
- Testing on upgraded facility → applied external B-field to IPG6-S → increased power absorption.

\[
m_{O_2} = 4.36 \text{mg/s} - p_{inj} = 13.63 \text{Pa} - p_{tank} = 0.42 \text{Pa}
\]

Inductive Plasma Thruster (IPT) Design Requirements

- $P_{in} < 5$ kW, ABEP variable mass flow, RF and contact-less $\rightarrow$ eliminate erosion issues;
- High exhaust velocity $\rightarrow$ EM acceleration $\rightarrow$ high ionization degree $\rightarrow$ helicon wave based plasma;
- Literature, HELIC, ADAMANT sim. $\rightarrow$ $f > 27.12$ MHz low pressure ignition and $n > 1 \times 10^{17} \text{m}^{-3};$
  - $f = 40.68$ MHz up to 4 kW acquired (Class-E amplifier).
- Started with a t-turn antenna $\rightarrow$ high reactance $X$ $\rightarrow$ high reflected power;
- The whole RF circuit need optimization.

\[
Z_s = 50 + j0 \Omega
\]

RF Generator (source)

Coax Cable 50 $\Omega$, $L \ll \lambda$

Dynamically converts $Z_L$ to 50+$j0 \Omega$

Matching Network

Coax Cable 50 $\Omega$, $L \ll \lambda$

Variable Impedance

$Z_L = Z_{iPT} = Z_{antenna} + Z_{plasma}$

IPT (load)

$P_{in}$

$Q_{diss}(P_{refl})$

$P_{in}, \text{IPT}$

$P_{refl}$
Inductive Plasma Thruster (IPT) Concept

- RF Generator
- Matching Network
- Tank
- Intake
- Discharge Channel
- Injector
- Electromagnet
- Electromagnet
- Electromagnet
- Acceleration Stage
- Power Supply
- Acceleration Stage Power Supply
- Neutral Plasma Exhaust
- Plasma
- Birdcage Antenna
Birdcage Antenna

- Used in MRI → At EPFL as plasma source for negative ion beam production → helicon waves measured;
- Sinusoidal distribution of the current around a cylindrical surface → homogenous transversal B-field;
- Designed to operate at resonance → reactance $X = 0 \ \Omega$;
- Two end-rings connected by N-legs: high pass, low pass, band pass configuration;
- Distribution of E and B → drift velocity to ions and electrons along same direction.

\[
I_{jk} = \begin{cases} 
\cos\left(\frac{2\pi j k}{N}\right), & k = 0,1,2, ..., N/2 \\
\sin\left(\frac{2\pi j k}{N}\right), & k = 1,2, ..., \left(\frac{N}{2} - 1\right) 
\end{cases}
\]
Birdcage Antenna Current Distribution

Current distribution along one rung (left) and along the whole birdcage (right) for N=10.

1

\[ I_n = \frac{I_0}{N} e^{i2\pi n} \]

-1

Normalized along one leg (rung) over time.

1

Normalized along birdcage for a given time.

\[ f(n) = \sin \pi n \]
Field configuration provides drift velocity for both ions and electrons along the same direction:

\[
\hat{\vec{v}}_E = \frac{1}{B^2} \begin{bmatrix}
\hat{x} & \hat{y} & \hat{z}
\end{bmatrix} = \frac{1}{B_0^2 + B_1^2} \begin{bmatrix}
0 \\ -E_1B_0 \\ E_1B_1
\end{bmatrix}
\]
• Each design has $N/2$ resonant modes (HP presents one resonance more: AR)

$$\omega_{k_{HP}} = \left[ C \left( L_{ER} + 2 L_{Leg} \sin^2 \frac{\pi k}{N} \right) \right]^{-1/2}, \quad (k = 0,1,2, ..., N/2)$$

• Only one resonance provides the required transversal homogenous B-field: $k = 1$;

• Conductive shield: isolation from the outside and *vice versa*;

• Once the IPT geometry is defined, the correct $C$ is extracted;

• 3D EM simulation tool used: XFdtd from Remcom Inc.
• 8 rungs/legs birdcage;
• Resonate at 40.68 MHz;
• Passively cooled;
• $P_{in} < 1.5$ kW;
• N-type RF connector;
• ISO-K DN100 standard;
Remcom Inc. XFdtd: full wave 3D electromagnetic analysis software
Frequency Response (example),

Tune antenna to have $k=1$ at the RF Generator frequency of 40.68 MHz
Impedance Analysis (example),
Resonance $X = 0 \Omega$

Only resonant mode that generates a linearly polarized magnetic field
\[ \vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2} \]

E-field and B-field are perpendicular.
Conclusions

- A new plasma thruster based on birdcage antenna has been designed;
- Ions and electrons pushed along the same direction → partial exhaust velocity, neutral plasma plume;
- High propellant flexibility → contact-less;
- RF shield provided;
- Tuning by magnetic field and moving injector → tuning and acceleration.

Outlook

- Capacitors installation and verification of resonance by network analyzer;
- First ignition by end of 2019 → plasma discharge characterization;
- Plasma diagnostic by Langmuir and Faraday probe at first, RPA and OES later.
Thank you for your kind attention, and for being here!

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