Miniature Vacuum Arc Thruster with Controlled Cathode Feeding

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6th International Workshop on Mechanisms of Vacuum Arcs, Jerusalem, Israel, 22nd March 2017
Outline

- Introduction
- Vacuum Arc Thruster
- Long Duration Vacuum Arc Thruster
- Summary and Future Plans
In the last years, considerable attention is given toward lowering cost and time in development of Earth observation and communication satellites.

Major mission cost factor is the mass required to be launched to orbit → smaller spacecraft are increasingly being used.

As a mass saving measure electric propulsion (EP) systems are being introduced to small spacecraft.
Introduction – EP Advantages

- EP offers higher propellant velocity $v_{ex}$ compared to chemical rockets

from the famous Rocket Equation

$$m_f = m_0 \exp(-\Delta v / v_{ex})$$

Higher propellant velocity saves propellant mass and volume

- Most EP propellant are safe to handle (non toxic, non explosive, easy storage)

\(\Delta v\) - s/c velocity change \hspace{1cm} m_f - s/c mass after burn \hspace{1cm} m_0 - s/c mass before burn
Introduction – EP Considerations

- EP requires an **additional power source**. Small spacecraft have limited available power due to mass and surface area restrictions.

<table>
<thead>
<tr>
<th>Pico, nano, micro and mini-satellites features</th>
<th>Pico</th>
<th>Nano</th>
<th>Micro</th>
<th>Mini-Small</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft mass</td>
<td>&lt; 1 kg</td>
<td>&lt; 10 kg</td>
<td>&lt; 100 kg</td>
<td>&lt; 450 kg</td>
</tr>
<tr>
<td>Payload mass</td>
<td>&lt; 0.1 kg</td>
<td>&lt; 1 kg</td>
<td>&lt; 30 kg</td>
<td>&lt; 200 kg</td>
</tr>
<tr>
<td>Power generated</td>
<td>&lt; 2 W</td>
<td>&lt; 20 W</td>
<td>&lt; 200 W</td>
<td>&lt; 600 W</td>
</tr>
</tbody>
</table>

- Although EP is inherently **low thrust** it can be utilized in most in-space missions.

<table>
<thead>
<tr>
<th>Electric propulsion missions</th>
<th>ΔV</th>
<th>flight time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit insertion</td>
<td>2000-5000 m/s</td>
<td>&lt; 180 days</td>
</tr>
<tr>
<td>Moon probe</td>
<td>~ 4000 m/s</td>
<td>~ 500 days</td>
</tr>
<tr>
<td>Station keeping</td>
<td>1-100 m/s</td>
<td>periodic</td>
</tr>
<tr>
<td>Drag compensation</td>
<td>10-1000 m/s</td>
<td>periodic</td>
</tr>
</tbody>
</table>
EP for Nanosatellites

- Nanosatellites (1 - 12 kg) are becoming popular platforms with large number of missions planned and flown.

- The most interesting aspect of nanosatellites is the ability to launch multiple platforms relatively inexpensively.

- Although each nanosatellite has limited resources, they can cooperate as a distributed system, provided they have an orbit control capability.

- Nanosatellite power level is restricted < 20 W therefore the current generation of EP systems cannot be used.

Kronhaus et al., *J. Spacecraft Rockets* 51, 2014
Vacuum Arc Thruster
Vacuum Arc Thruster Working Principles

Pulsed thruster based on metal ablation

- Vacuum arc is a discharge that burns in metal vapor, liberated from the cathode into an interelectrode gap initially at vacuum
- Combination of Joule heating and ion bombardment heating sustains the temperatures required to emit electrons and vaporize cathode material
- Produces high velocity, highly ionized metal plasma flows
- No external magnetic field is needed for operation
- Discharge is maintained through one or more highly mobile, luminous spots

Schein et al., Sci. Rev. Instrum. 73, 2002
The plasma originates from small cathode spots (crater radius 1 - 10 μm) that move rapidly and randomly on the cathode surface.

Spot motion is the result of the appearance of a new spot and the death of its predecessor.

Electrons are emitted by field enhanced thermionic emission.

A single spot is formed in low current operation (1 - 100 A).

Spot lifetime is < 0.1 μs.

The plasma is fully ionized.

The plasma density close to the cathode surface is nearly the density of the solid.

Plasma acceleration by gas kinetic expansion to velocities of $\sim 10^4 \text{ m/s}$.

The plasma jet ions carries $\approx 10\%$ of the discharge current.

Plasma jet has quasi-cosine distribution - directed perpendicular to the metal surface.

<table>
<thead>
<tr>
<th>Cathode Material</th>
<th>Ion velocity [m/s]</th>
<th>Electron temp [eV]</th>
<th>Ion charge state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>12,500 - 12,800</td>
<td>2 - 3.5</td>
<td>2</td>
</tr>
<tr>
<td>Mo</td>
<td>15,500 - 17,400</td>
<td>4.5</td>
<td>3.1</td>
</tr>
<tr>
<td>W</td>
<td>10,500</td>
<td>4.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Ti</td>
<td>13,000 - 22,200</td>
<td>2 - 3.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Al</td>
<td>27,600</td>
<td>3.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

VAT Triggerless Ignition

- The VAT requires a reliable low mass and low power arc ignition mechanism - this is provided by the triggerless ignition method.
  

- A thin conducting film on the insulator provides high, but finite, resistance between cathode and anode.

- With few hundred volts between the electrodes breakdown occurs at very small gaps in the thin metal film.

- Tiny discharges produce enough metal vapor to initiate the main discharge in the gap.
A light weight and simple processing unit (PPU) < 100 g

The PPU requires only low voltage dc input

A capacitor buffers the s/c bus from high current operation

A solid state switch is used to short/open an inductor, therefore producing the high voltage necessary for triggerless ignition

Pulse energy and frequency are controlled by gate signal

Schein et al., Rev. Sci. Instrum. 73, 2002
Process of VAT Triggerless Ignition

ICCD image of a triggerless ignition process (in atm. pressure)

Typical measured I-V curve of the discharge. Arc onset > 1 A

Kronhaus et al., Scitech 2017, AIAA 2017-0159
Triggerless Vacuum Arc Thruster - Electrical Characteristics

Triggerless VAT discharge characteristics (Cu cathode, input voltage 25 V, pulse energy 150 mJ):

Arc current-voltage

Input current-voltage
Ion current density distribution measured by biased planar probes positioned on a spherical cap of 60 deg half angle and 0.118 m radius

Kronhaus et al., 33rd IEPC, IEPC-2013-195
Vacuum Arc Thruster Disadvantages

- The VAT is a pulsed device and its lifetime is determined by the number of ignitions.

- Current VAT designs are capable of ~ 20,000 pulses, lifetime limited by:
  - Change in cathode-insulator-anode interface geometry due to cathode erosion
  - Destruction of the conductive coating layer on the insulator surface

- Classical VAT lifetime is insufficient to meet propulsion requirements.
Long Duration Vacuum Arc Thruster
Inline Screw Feeding Vacuum Arc Thruster

- An advanced vacuum arc thruster concept, with an extended lifetime, is being developed in the APL, Technion. Patented in 2016.

- The ISF-VAT has a controlled feeding mechanism based on screw action (spiral spring and piezoactuator)

- The cathode is moved towards the exit plane in a helical path – uniform erosion

- Constant geometry is maintained → Metal vapor and droplets, eroded from the cathode, replenish the thin conducting layer on the insulator

ISF-VAT Feeding Mechanism

- The actuation frequency of the piezoactuator controls the release of the spring and hence the feeding rate
  \[ \nu_{\text{feed}} = \Delta l f_{\text{feed}} \]

- Although the actuator performs the same break action, the torque of the spring decreases with the turns producing a non linear behavior of \( \Delta l(l) \)

![Graph showing the measured variation of the discrete length advance \( \Delta l \) versus cathode advancement length \( l \)]
To achieve a constant feeding rate, the actuation frequency can be modified according to:

\[ v_{\text{feed}} = \Delta l(l) f_{\text{feed}}(l) = \text{const} \]

The cathode mass flow rate \( m_{\text{cathode}} \) is related to the feeding rate by:

\[ m_{\text{cathode}} = v_{\text{feed}} \rho S \]

where \( \rho \) is the cathode mass density and \( S \) the cathode cross sectional area.

The mass flow rate can be estimated by Ti erosion rate \( E_r \approx 30 \, \mu\text{g}/\text{C} \) and discharge parameters:

\[
\begin{align*}
    f_{\text{arc}} &= 30 \, \text{Hz} \\
    V_{\text{arc}} &= 30 \, \text{V} \\
    \epsilon_{\text{arc}} &= 0.1 \, \text{J} \\
    m_{\text{est\,cathode}} &= E_r \frac{\epsilon_{\text{arc}}}{V_{\text{arc}}} f_{\text{arc}} \approx 3 \, \mu\text{g}/\text{s}
\end{align*}
\]
APL is part of the Faculty of Aerospace Engineering and is located in the Asher Space Research Institute, Technion.

The centerpiece of the Aerospace Plasma Laboratory is the vacuum test facility. It is a cylindrical vacuum chamber, 1.0 m long and 0.6 m in diameter. Ultimate pressure is $10^{-7}$ mbar.

The vacuum chamber design provides great flexibility in the equipment that can be installed inside and outside of the chamber.

A number of specialized diagnostic tools are available including a micro-Newton thrust balance.
Experimental Setup
Experimental Results – Thrust Measurement

ISF-VAT operation in the APL vacuum test facility (click for movie)

A 10 min sample of thrust measurement data obtained by operating the ISF-VAT at $f_{arc} = 30$ Hz, Ti cathode
Experimental Results – Mass Flow Rate Measurement

Steady state ISF-VAT cathode mass-flow-rate at different discharge power levels, Ti cathode

<table>
<thead>
<tr>
<th>$f_{\text{arc}}, \text{Hz}$</th>
<th>$P_{\text{arc}}, \text{W}$</th>
<th>$m_{\text{cathode}}, \mu\text{g/s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30$</td>
<td>$3\pm0.6$</td>
<td>$1.8\pm0.35$</td>
</tr>
<tr>
<td>$15$</td>
<td>$1.5\pm0.3$</td>
<td>$0.9\pm0.18$</td>
</tr>
<tr>
<td>$5$</td>
<td>$0.5\pm0.1$</td>
<td>$0.29\pm0.05$</td>
</tr>
</tbody>
</table>

![Graph showing mass flow rate over time for different arc frequencies.](image)
Experimental Results Cont.

- The ISF-VAT experimental model demonstrated operation of more than $10^6$ pulses in a single run!

- Experiments show that operating at the correct mass flow rate, selected according to cathode material and diameter, total erosion of the cathode tip is obtained.

- Cathode geometry is maintained and uniform coating is produced on the insulator enabling the process to continue.

The cathode tip shows a symmetric, spear shaped, erosion pattern.
ISF-VAT Specifications and Performance

- Compact and robust design 15 X 15 X 65 mm³
- Directed thrust ≈ 50 % of the plume in a 45 deg half-angle
- Mass flow rate of ~ 1 μg/s @ 3 W
- Electrical efficiency independent of power ~ 1 %
- Power processing unit (PPU) mass ~ 100 g

Performance figures of the new thruster

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average thrust, μN</td>
<td>1 - 25</td>
</tr>
<tr>
<td>Specific impulse, s</td>
<td>400 - 600</td>
</tr>
<tr>
<td>Total input power, W</td>
<td>0.5 - 10</td>
</tr>
<tr>
<td>Total impulse, Ns</td>
<td>0.2 - 1</td>
</tr>
<tr>
<td>Mass per thruster head, g</td>
<td>~ 60</td>
</tr>
</tbody>
</table>
Summary and Future Plans

- A miniaturized long-duration VAT was designed in APL termed ISF-VAT.
  - Thruster mass flow rate is fully controlled
  - Erosion coating processes are balanced in steady state
  - Interface geometry constant → performance is preserved
  - The thruster does not require external magnetic field for its operation

- Preliminary results of the ISF-VAT show promise to provide basic propulsion capability for nanosatellites

- Research is ongoing in APL to further improving ISF-VAT lifetime. A model is needed for the insulator conducting layer deposition and erosion processes
Thank You!