Miniature Vacuum Arc Thruster with Controlled Cathode Feeding

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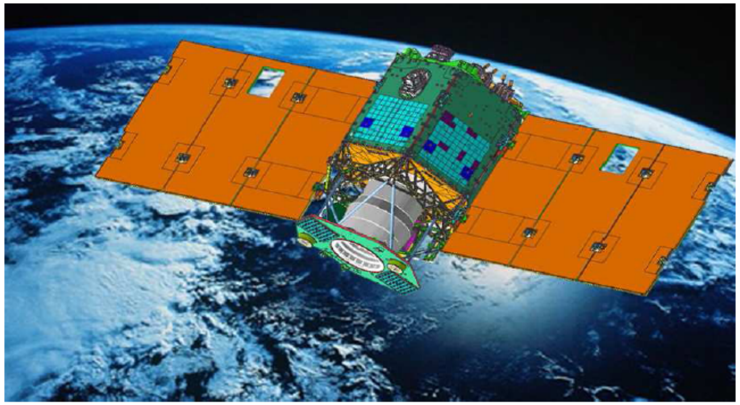
6th International Workshop on Mechanisms of Vacuum Arcs,
Jerusalem, Israel, 22nd March 2017

Outline

- Introduction
- Vacuum Arc Thruster
- Long Duration Vacuum Arc Thruster
- Summary and Future Plans

Introduction

- 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



VENμS, Israel Space Agency

SMART-1 moon probe, ESA

Introduction – EP Advantages

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- 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)

Δv - s/c velocity change

m_f - s/c mass after burn

m_0 - s/c mass before burn

Introduction – EP Considerations

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

Pico, nano, micro and mini- satellites features

	Pico	Nano	Micro	Mini-Small
Spacecraft mass	< 1 kg	< 10 kg	< 100 kg	< 450 kg
Payload mass	< 0.1 kg	< 1 kg	< 30 kg	< 200 kg
Power generated	< 2 W	< 20 W	< 200 W	< 600 W

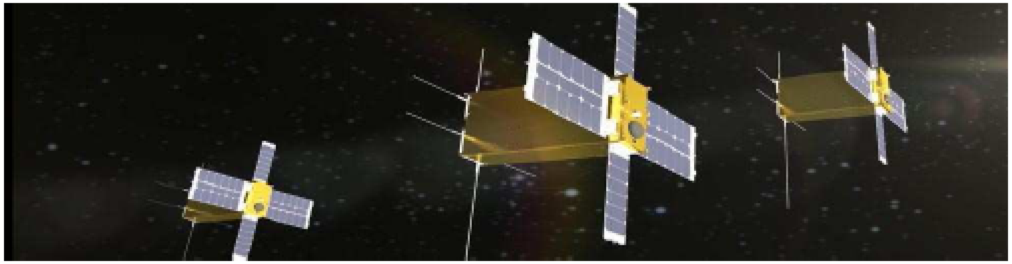
- Although EP is inherently low thrust it can be utilized in most in-space missions

Electric propulsion missions

Mission	ΔV	flight time
Orbit insertion	2000-5000 m/s	< 180 days
Moon probe	~ 4000 m/s	~ 500 days
Station keeping	1-100 m/s	periodic
Drag compensation	10-1000 m/s	periodic

EP for Nanosatellites

- Nanosatellites (1 - 12 kg) are becoming poplar 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



SAMSON, Technion

proposed NetSat, Wuerzburg University

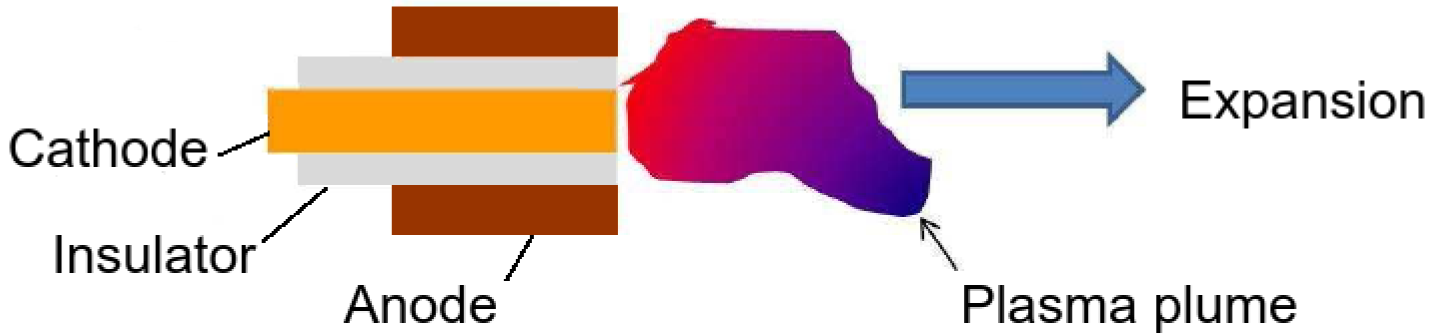
Kronhaus et al., *J. Spacecraft Rockets* **51**, 2014

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

VAT Physics – Cathode Spot Characteristics

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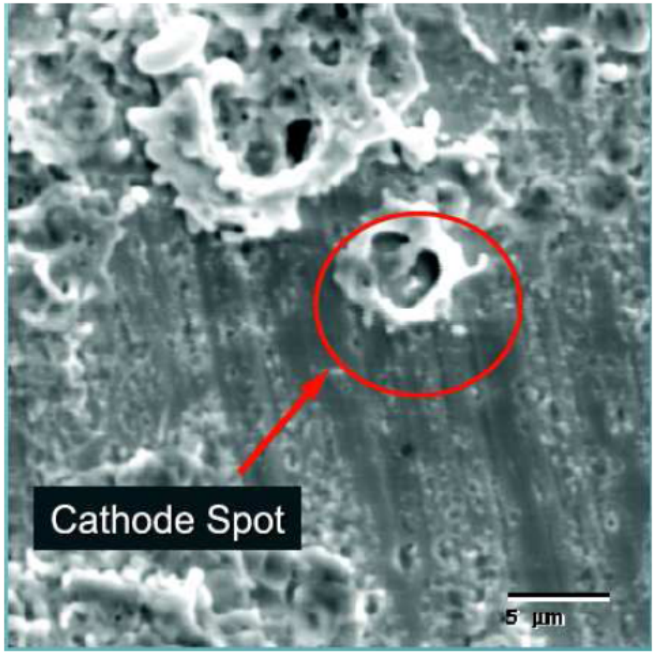
- The plasma originates from small cathode spots (crater radius 1 - 10 μm) that move rapidly and randomly on the cathode surface
- Spot motion is the result of the appearance of a new spot and the death of its predecessor
- Electrons are emitted by field enhanced thermionic emission
- A single spot is formed in low current operation (1 - 100 A)
- Spot lifetime is < 0.1 μs



Beilis, IEEE Trans. Plasma Sci., 2001

VAT Physics – Plasma Plume Characteristics

- 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 ~ 10^4 m/s
- The plasma jet ions carries ≈ 10 % of the discharge current
- Plasma jet has quasi-cosine distribution - directed perpendicular to the metal surface

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

Polk et al., *IEEE Trans. Plasma Sci.* **26**, 2008

VAT Triggerless Ignition

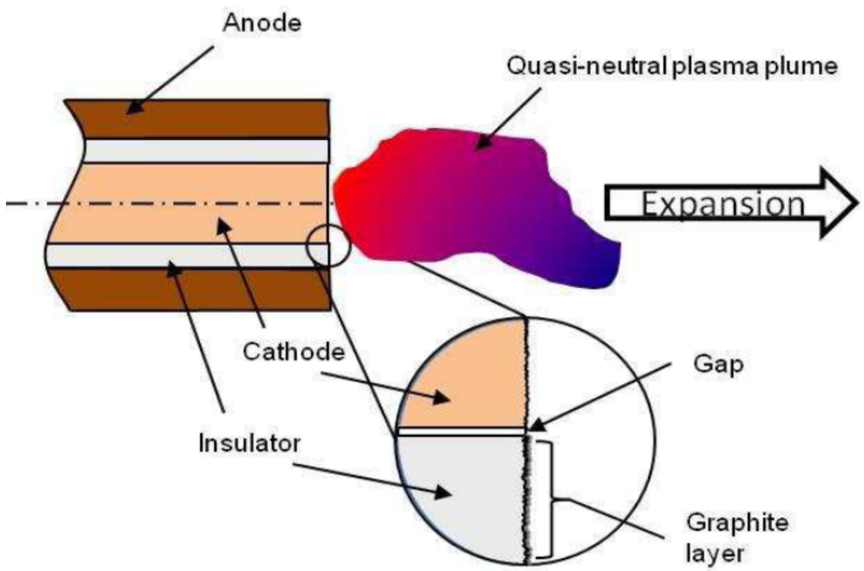
- The VAT requires a reliable low mass and low power arc ignition mechanism - this is provided by the triggerless ignition method

  Anders et al., *Rev. Sci. Instrum.* **71**, 2000

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

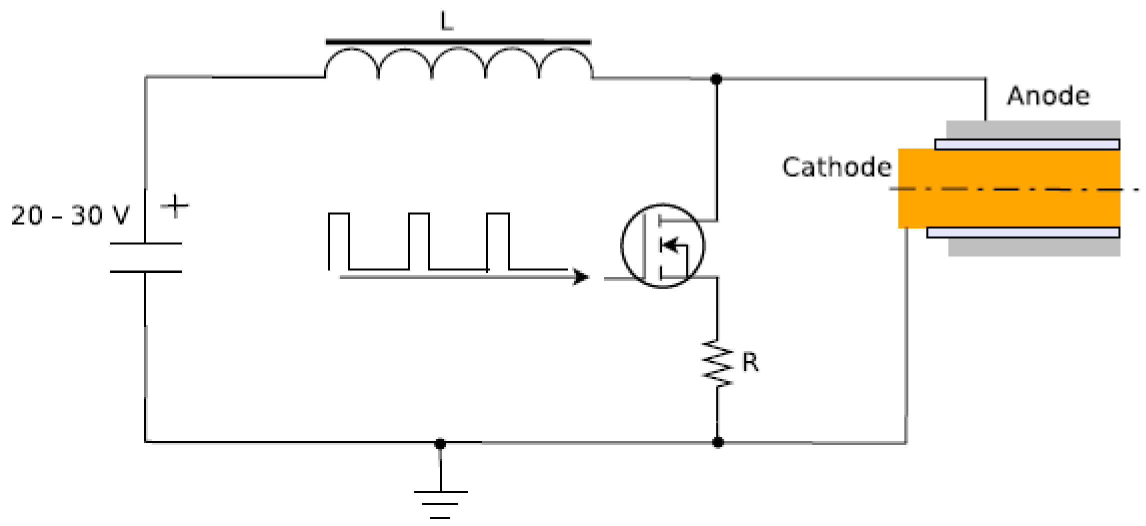
- With few hundred volts between the electrodes breakdown occurs at very small gaps in the thin metal film

- Tiny discharges produce enough metal vapor to initiate the main discharge in the gap



Triggerless VAT Power Processing Unit

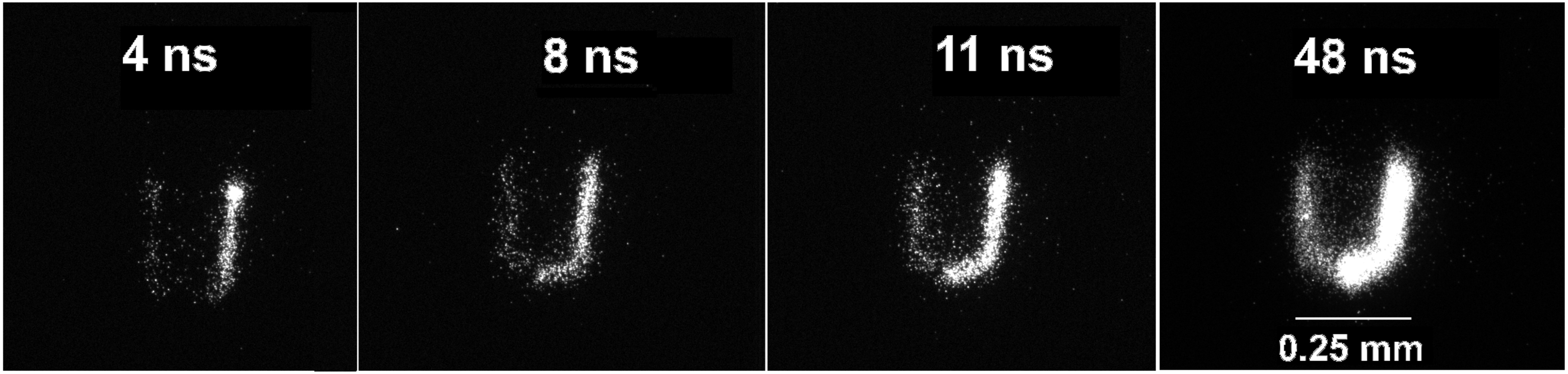
- A light weight and simple processing unit (PPU) < 100 g
- The PPU requires only low voltage dc input
- A capacitor buffers the s/c bus from high current operation
- A solid state switch is used to short/open an inductor, therefore producing the high voltage necessary for triggerless ignition
- Pulse energy and frequency are controlled by gate signal

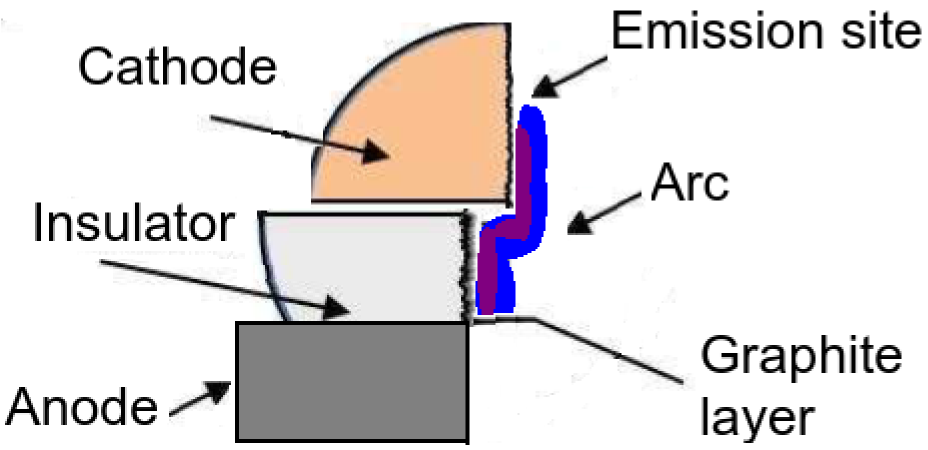


Schein et al., *Rev. Sci. Instrum*. **73**, 2002

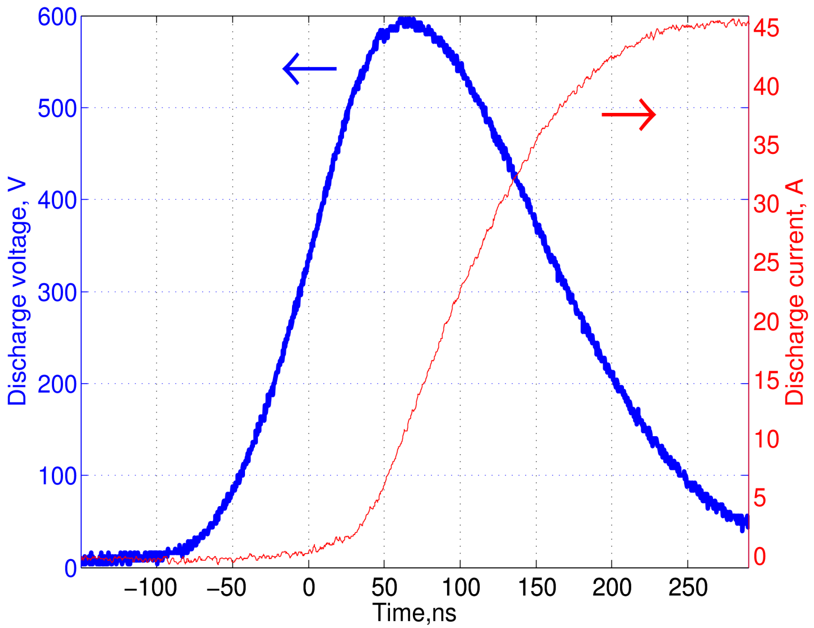
Process of VAT Triggerless Ignition

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





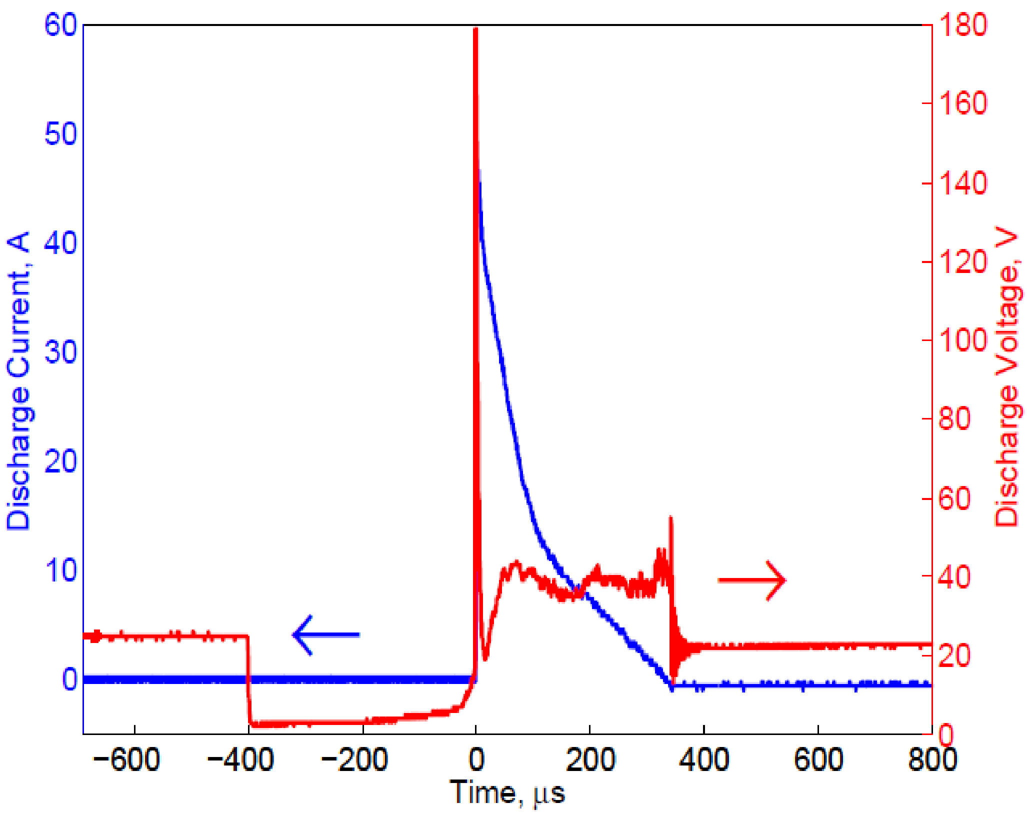
Kronhaus et al., Scitech 2017, AIAA 2017-0159



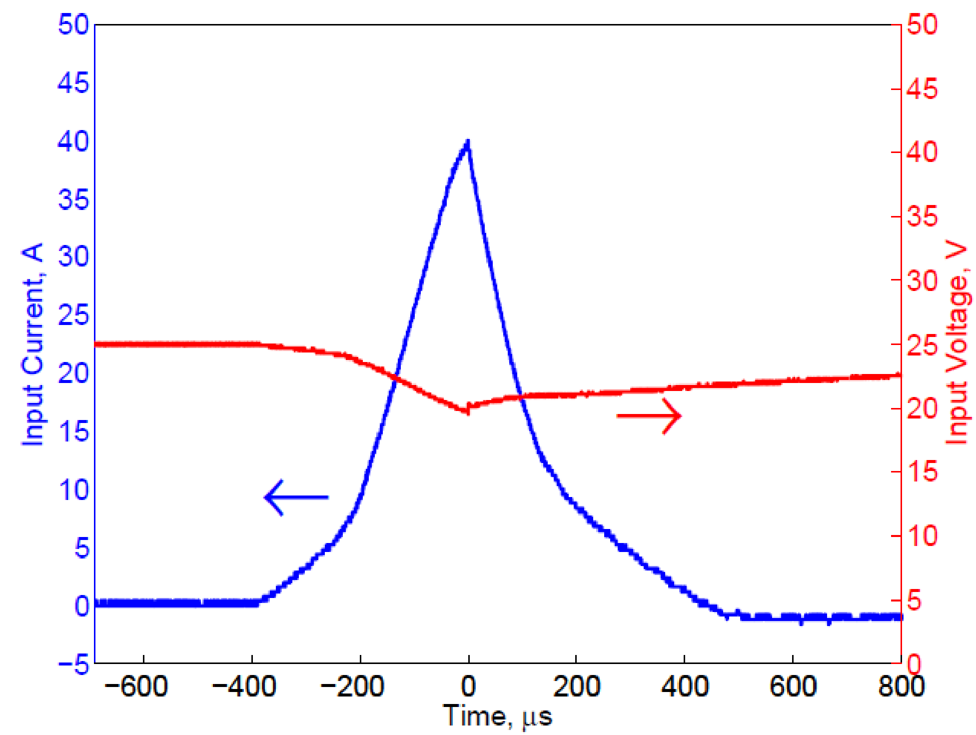
Typical measured I-V curve of the discharge. Arc onset > 1 A

Triggerless Vacuum Arc Thruster - Electrical Characteristics

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

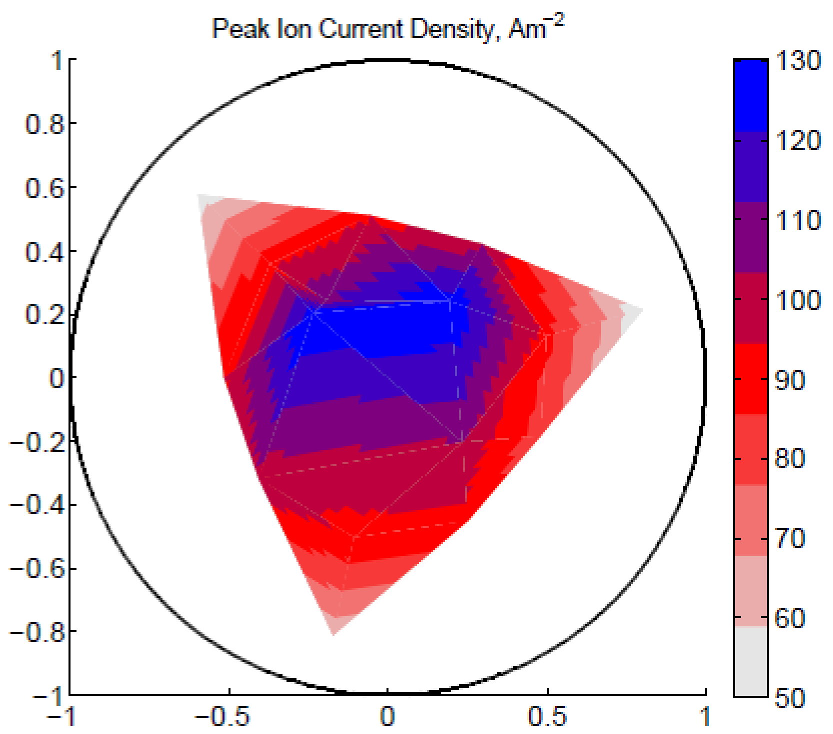


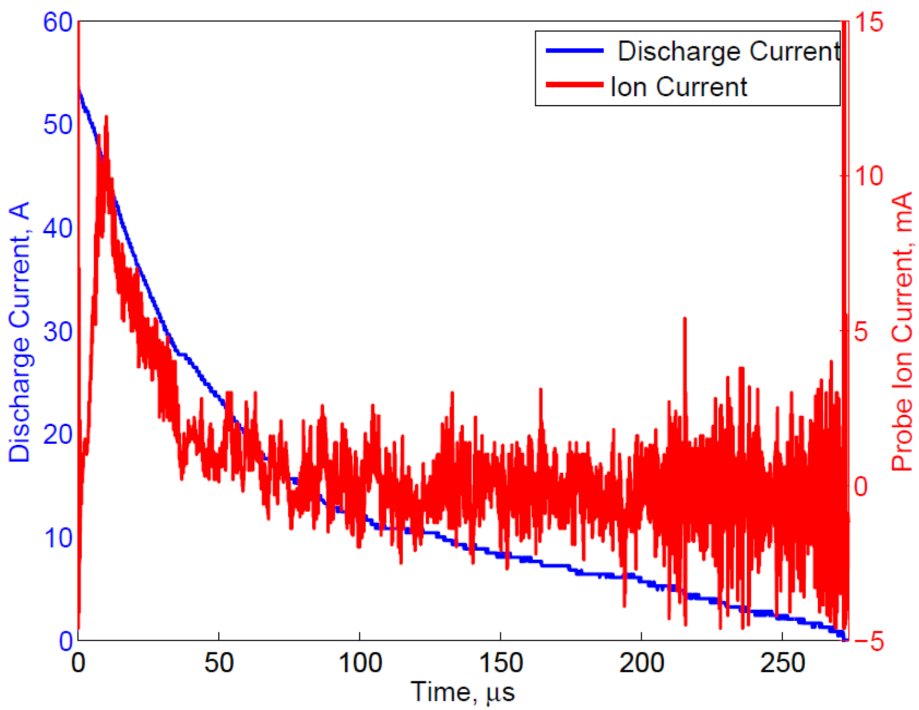
Arc current-voltage



Input current-voltage

Triggerless Vacuum Arc Thruster - Plume Measurement Results





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

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- 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:

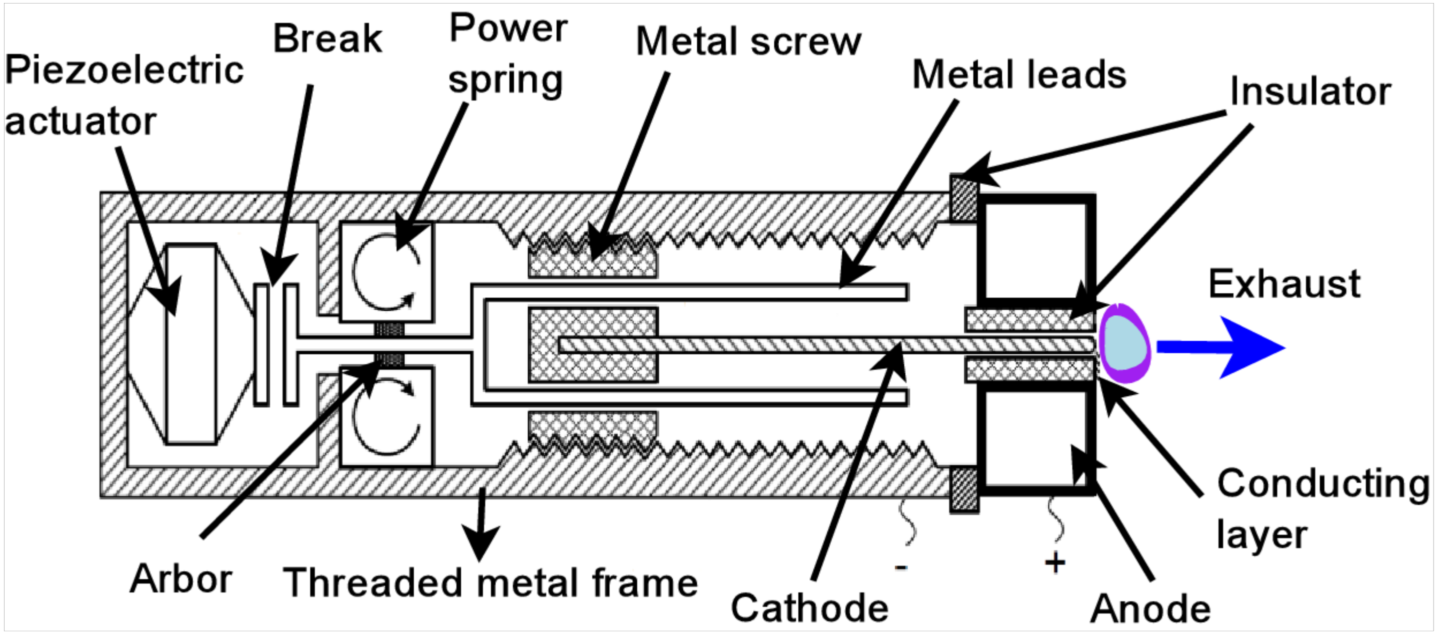
  - Change in cathode-insulator-anode interface geometry due to cathode erosion
  - Destruction of the conductive coating layer on the insulator surface

- 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 life time, 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



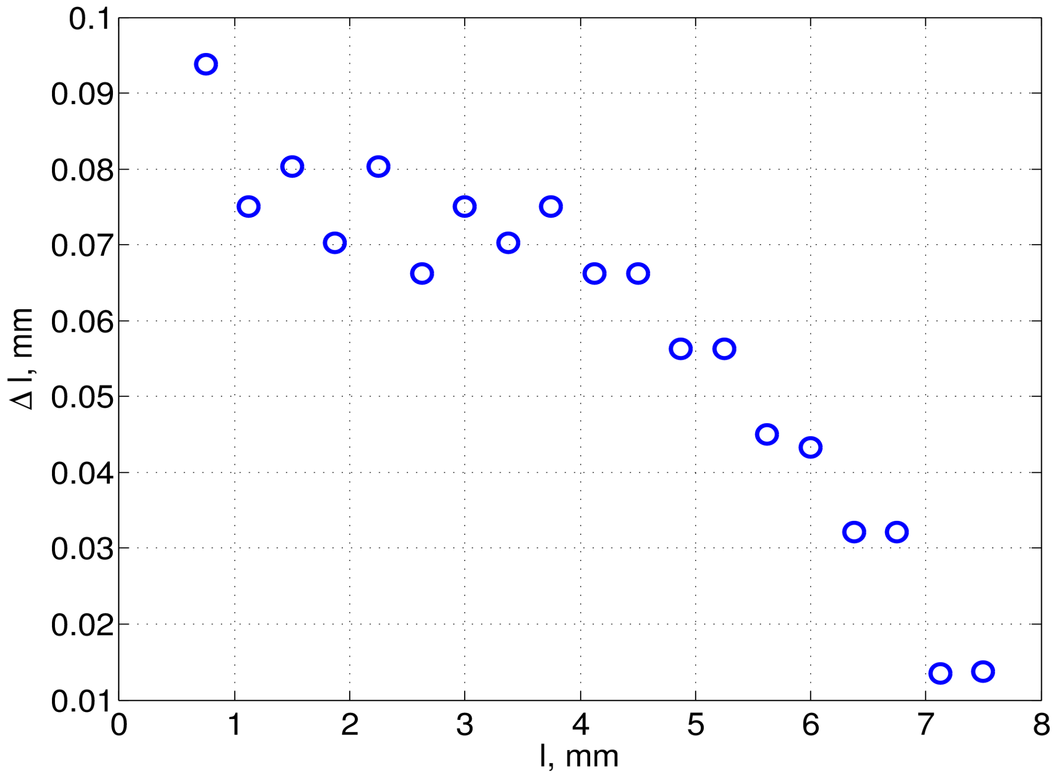
Kronhaus et al., *Rev. Sci. Instrum.*, 2017

ISF-VAT Feeding Mechanism

- The actuation frequency of the piezoactuator controls the release of the spring and hence the feeding rate

$$v_{\text{feed}} = \Delta l f_{\text{feed}}$$

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



Measured variation of the discrete length advance Δl versus cathode advancement length l

ISF-VAT Feeding Mechanism Cont.

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- To achieve a constant feeding rate, the actuation frequency can be modified according to:

$$v_{\mathrm{feed}} = \Delta l(l) f_{\mathrm{feed}}(l) = const$$

- The cathode mass flow rate $\dot{m}_{\mathrm{cathode}}$ is related to the feeding rate by:

$$\dot{m}_{\mathrm{cathode}} = v_{\mathrm{feed}} \rho S$$

where ρ is the cathode mass density and S the cathode cross sectional area

- The mass flow rate can be estimated by Ti erosion rate $E_r \approx 30\ \mu\mathrm{g/C}$ and discharge parameters

$$f_{arc} = 30\ \mathrm{Hz}$$

$$V_{\mathrm{arc}} = 30\ \mathrm{V}$$

$$\epsilon_{\mathrm{arc}} = 0.1\ \mathrm{J}$$

$$\dot{m}^{\mathrm{est}}_{\mathrm{cathode}} = E_r \frac{\epsilon_{\mathrm{arc}}}{V_{\mathrm{arc}}} f_{\mathrm{arc}} \approx 3\ \mu\mathrm{g/s}$$

Experimental Setup/Aerospace Plasma Laboratory

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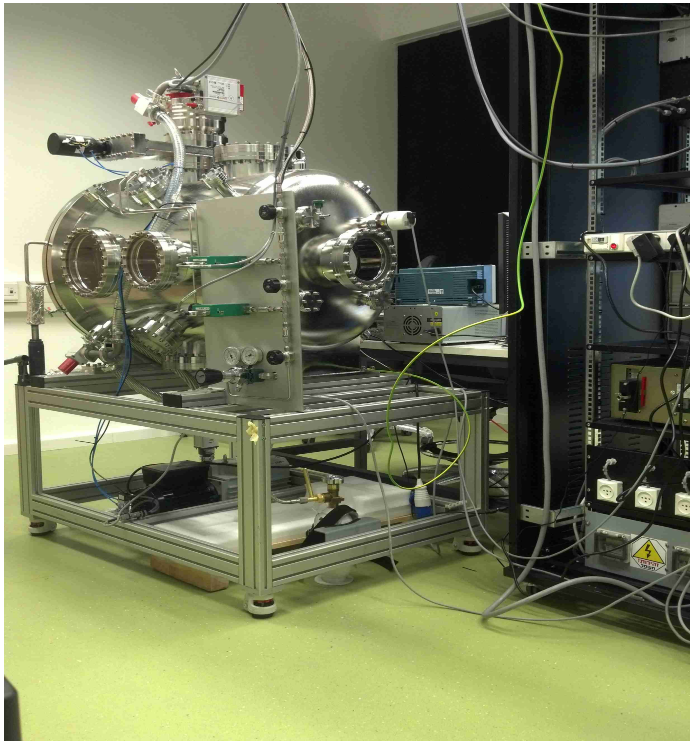
- APL is part of the Faculty of Aerospace Engineering and is located in the Asher Space Research Institute, Technion
- The centerpiece of the Aerospace Plasma Laboratory is the vacuum test facility. It is a cylindrical vacuum chamber, 1.0 m long and 0.6 m in diameter. Ultimate pressure is 10^{-7} mbar
- 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

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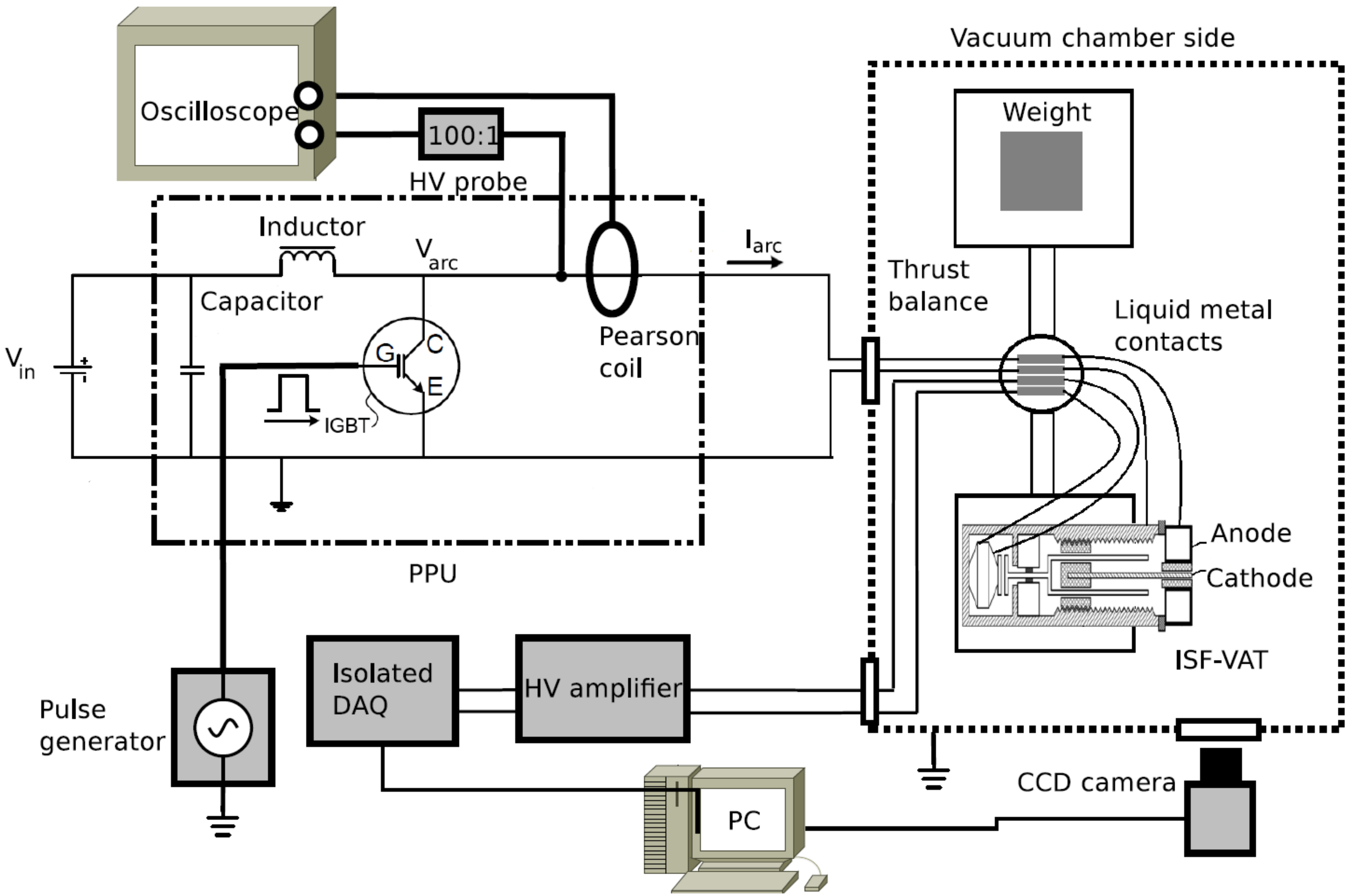
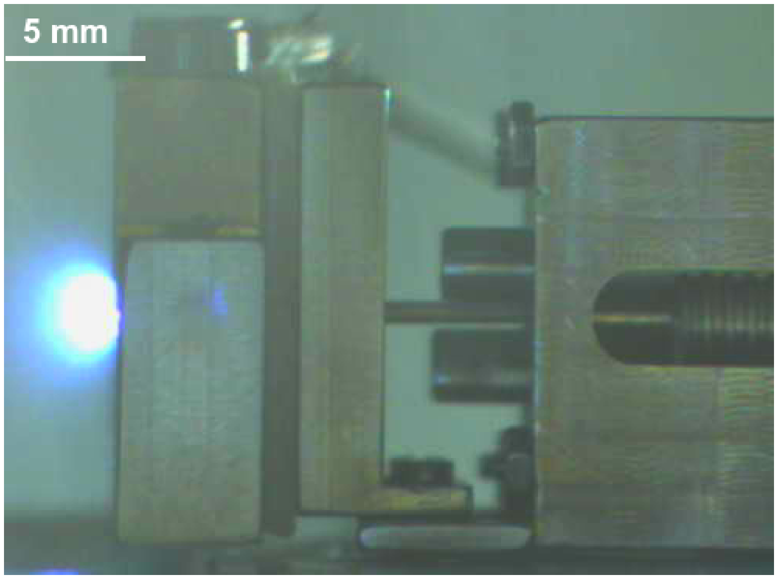
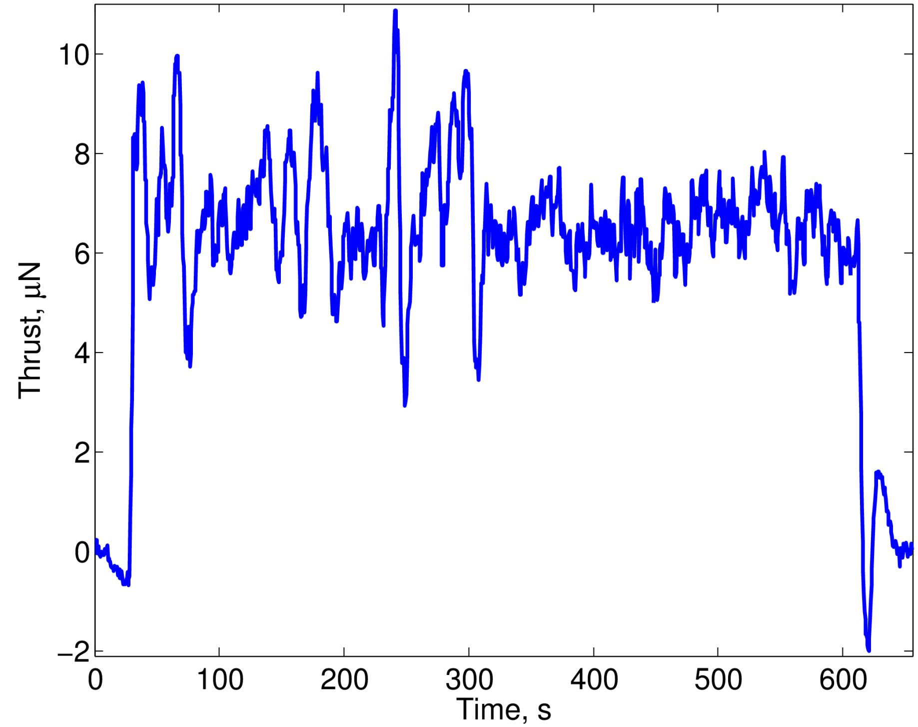


Experimental Results – Thrust Measurement



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

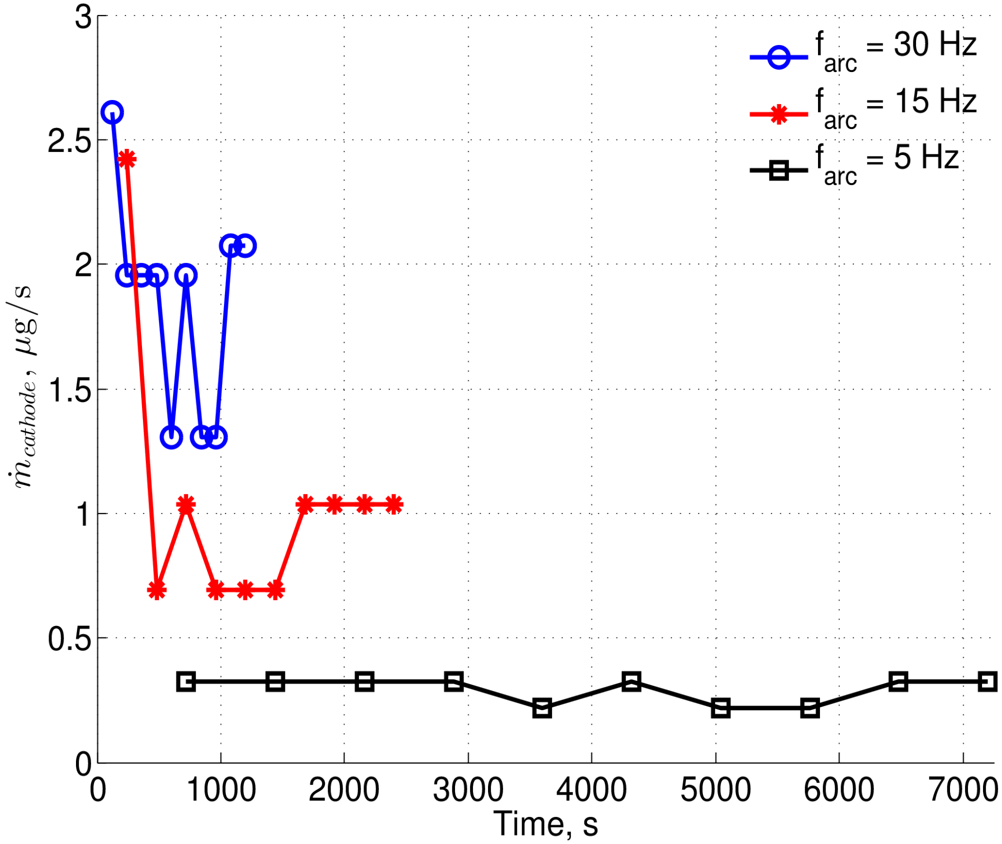


A 10 min sample of thrust measurement data obtained by operating the ISF-VAT at f_{arc} = 30 Hz, Ti cathode

Experimental Results – Mass Flow Rate Measurement

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

f_{arc}, Hz	P_{arc}, W	$\dot{m}_{\mathrm{cathode}}$, μg/s
30	3 ± 0.6	1.8 ± 0.35
15	1.5 ± 0.3	0.9 ± 0.18
5	0.5 ± 0.1	0.29 ± 0.05



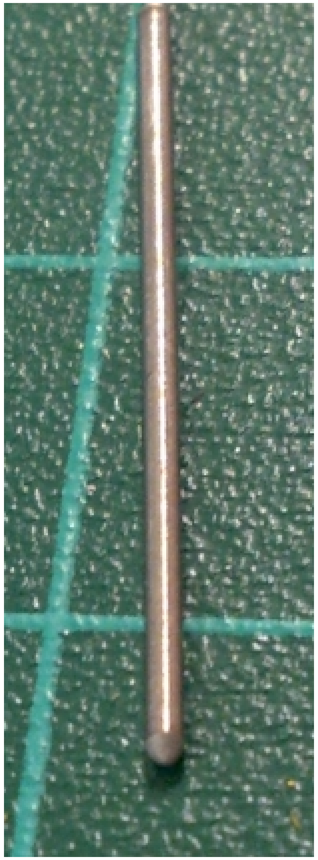
Experimental Results Cont.

- 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

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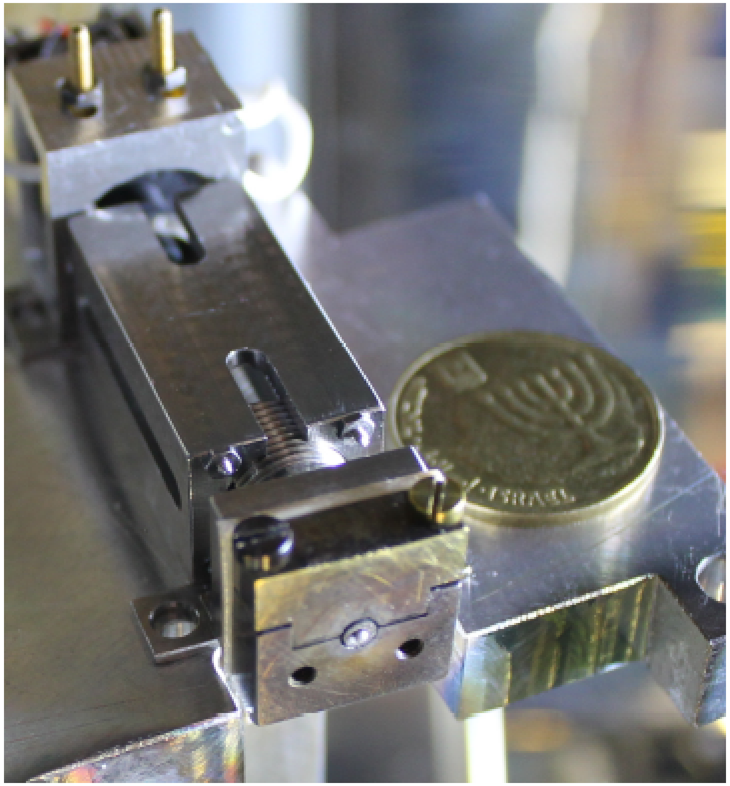
- Compact and robust design 15 X 15 X 65 mm^3
- Directed thrust ≈ 50 % of the plume in a 45 deg half-angle
- Mass flow rate of ~ 1 μg/s @ 3 W
- Electrical efficiency independent of power ~ 1 %
- Power processing unit (PPU) mass ~ 100 g

Performance figures of the new thruster

Parameter	Value
Average thrust, μN	1 - 25
Specific impulse, s	400 - 600
Total input power, W	0.5 - 10
Total impulse, Ns	0.2 - 1
Mass per thruster head, g	~ 60



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

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Thank You!