Low Mass Vacuum Arc Thruster System for Station Keeping Missions*†

Jochen Schein, Niansheng Qi, Robert Binder, Mahadevan Krishnan
Alameda Applied Sciences Corp, 2235 Polvorosa Ave, San Leandro, CA 94577, (510) 483-4156 schein@aasc.net

John K. Ziemer, James E. Polk
NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, (818) 354-9275
james.e.polk@jpl.nasa.gov

André Anders
Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, (510) 486-6745
aanders@lbl.gov

IEPC-01-228

A vacuum arc thruster (VAT) in combination with an innovative inductive energy storage power processing unit (PPU) has been developed for microspacecraft propulsion. The VAT can be operated with a variety of materials, each of which provides ions with a different specific impulse ranging from 1100s for Ta to close to 3000s for Al. Initiation of the arc requires only a few hundred volts due to the innovative 'triggerless' approach in which a conductive layer between the cathode and the anode produces the initial charge carriers needed for plasma production. The initial starting voltage as well as the energy to operate the vacuum arc is generated by a low mass (<300 g) inductive energy storage PPU, which can be controlled with TTL level signals. Calculations have shown that the expected thrust efficiency can reach up to 18µN/W for tungsten.

The VAT has been tested at JPL to verify the predicted performance using Ti as cathode material. Thrust measurements with a resolution down to 1µN-s showed thrust/power values of 2.2µN/W, versus a predicted value of 6.7µN/W The large discrepancy is explained by the very non-ideal electrode geometry that was used. With optimized geometry, it is expected that the VAT can achieve ≈12 to 13% overall efficiencies with Ti and W cathodes.

Introduction

The development of micro- and nano-satellites is presently of strong interest to the Air Force and NASA.[1-3] The design of a micro-spacecraft affects the propulsion system by limiting its power, mass and fuel system complexity. The advanced propulsion systems that are required for orbit transfer and station keeping will extend the lifetime of the satellites, maximize payload and minimize launch costs. For future space missions, micro- and nano-propulsion could be an enabling factor in space force enhancement, space control and space force applications.

New types of micro- and nano-thrusters should offer a wide range of impulse bits from nN-s to µN-s at overall thrust efficiencies ~20%, with very low (<1 kg) total thruster and PPU mass. Scaling existing electric propulsion engines such as Xe ion engines and Hall thrusters down to ~1-10 W power levels is not practical. The unavoidable overhead mass of propellant storage tank, flow controls and plumbing in Xe ion engines and the increasing magnetic field with decreasing size in Hall thrusters makes their overall efficiency unacceptably low at these power levels. Other candidate electric propulsion engines that might be scaled down include the micro-colloid thruster, itself an evolution of the Field Emission Electric Propulsion thruster, and the macro-field ionization thruster. Both these electrostatic thrusters are at an early stage of development. The PPT has been shown to be a good candidate for many missions requiring ~µN-s to mN-s impulse bits.[4] This type of thruster may also be scaled down in current and power to deliver nN-s impulse bits. However, the low propellant utilization efficiency of PPTs (due to late time ablation from the Teflon™ insulator) and their requirement for high peak operating voltages (~2 kV) makes their

---

* Presented as Paper IEPC-01-228 at the 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October, 2001.

thrust efficiency <10%. In addition, the use of a bulky high voltage capacitor in the PPU reduces their thrust/mass ratio considerably as the overall power and thrust are scaled down. The vacuum arc micro-thruster (VAT) with an inductive energy storage PPU that is described in this paper, is a low mass alternative that promises to overcome these limitations and could become the thruster of choice for many micro- and nano-satellite missions.

The vacuum arc plasma source [5-7] is a good candidate as a thruster. Ions of any of the solid metals of the periodic table, as well as metallic compounds and alloys can be produced.[8] Fully ionized metal plasma is produced by a vacuum arc discharge from a macroscopically cold cathode. The metal plasma plume, produced at cathode spots streams outward to achieve velocities of 1-3 x10^6 cm/s over a wide range of elements from Carbon to Tungsten, making the VAT suitable for 1000-3000 s specific impulse missions. Time-of-flight measurements of the charge state distributions have shown that the ions are predominantly of charge states 1+ to 3+ depending on the metal species used and the arc power density.[9] Arc discharges are produced with arc currents from tens of amperes to many kA. Pulse lengths can be from a few microseconds upwards, and the pulse repetition rate can readily be up to a few hundred pulses per second. This implies a very wide dynamic thrust range. The VAT can be operated in a pulsed mode with an average power of 1-100 W and masses of about 0.1 kg. For orbit transfer and orbit maneuvering of a satellite, high thrusts are desired to save time, while for station keeping the required thrusts are relatively low. The VAT has the potential of providing a wide dynamic range of thrusts without efficiency loss for these missions.

This paper describes feasibility studies of the VAT. We have characterized the arc source I-V curve, plasma streaming velocity, arc ion flux and cathode erosion rate. Several cathode elements have been evaluated as propellants. We have demonstrated that the arc is stable at current levels as low as ≈10 A and a voltage drop of few tens of volts. From these measurements, the energy efficiency and the thrust of the VAT were derived and compared to thrust measurements. The preliminary results indicate that the VAT is a promising new candidate for space micro-propulsion applications.

Experimental Apparatus

Initial production of plasma poses a technological challenge for any kind of plasma device. Typically, this plasma initiation requires a separate, high voltage trigger pulse, which in turn results in an additional mass overhead to the thruster and produces unnecessary electromagnetic interference and handling problems.

AASC has found a way to overcome this obstacle by using the so called ‘self-triggered’ or ‘triggerless’ approach [10]. In Figure 1 the ‘self-triggered’ principle is shown using a pulse-forming-network (PFN).

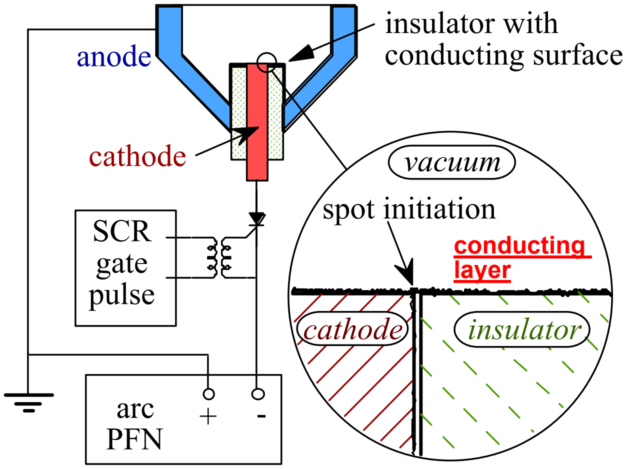

Figure 1: Principle of triggerless ignition

The layer separating the cathode from the anode was coated with a thin conducting film of graphite. When the relatively low voltage (≈100V-200V) arc power supply was switched with a solid state switch, a current through this conducting layer was produced which was concentrated at the contact points with the cathode. Plasma from these contact points expands into the vacuum gap and supports conduction from cathode to anode across the vacuum gap. Because the resistance of the conducting film is ~1000 Ω, the current is quickly shunted from the initial (surface) path to the vacuum gap. Erosion during ignition and re-deposition of the plasmas over the insulator during the arc discharge makes it possible to conduct over 10^6 pulses with such an arc trigger mechanism without failure.

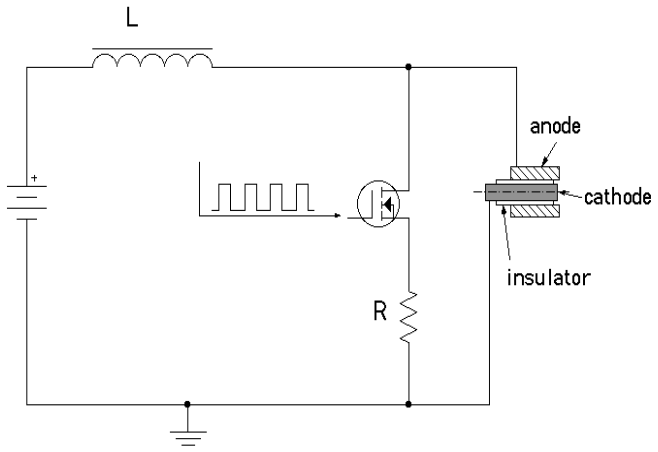

Figure 2: Schematic drawing of the coaxial vacuum arc assembly driven by the IES PPU

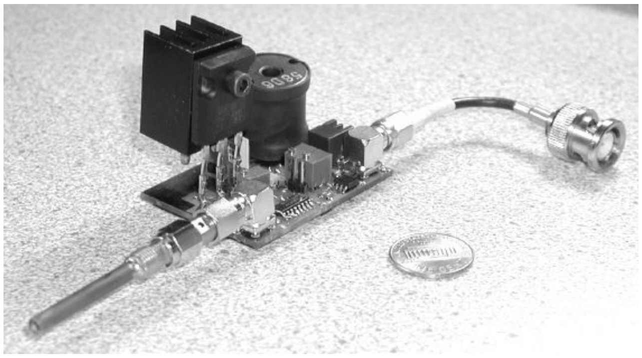

Figure 3: Picture of VAT including PPU. The thruster head is located to the left of the PPU.

Use of the self-triggered vacuum arc enables use of a low mass PPU that uses inductive energy storage (IES). Figures 2 and 3 show a schematic drawing of VAT and a photograph of the first prototype of the PPU, respectively.

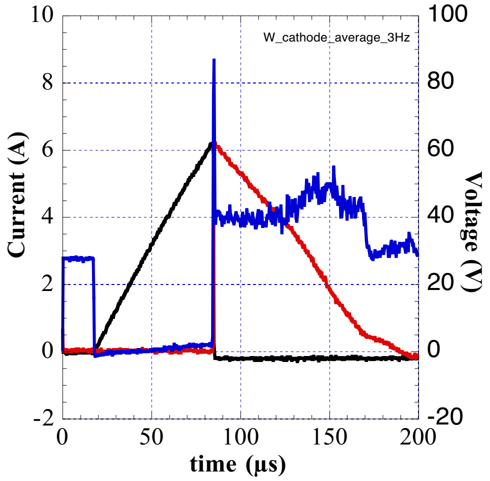

Fig. 4: Measured voltage (blue), current through the IGBT (black) and arc current (red) of a W arc.

A semiconductor switch is triggered to draw a current I from a DC power supply (5V-35V) through an inductor L. The moment the switch opens, a voltage peak L dI/dt is produced which ignites the arc by driving current through the thin-film coating on the ceramic between anode and cathode. Subsequently plasma is established at a hot spot at the cathode-coating interface and the stored energy in the inductor supports the plasma. Figure 4 shows the current and voltage traces of the IES-PPU-driven VAT.

Since no high voltage energy storage capacitors are required for this circuit, the driver is compact, low-mass and has long lifetime. The mass of this VAT is ~60 g for the driver and ~30 g for the arc source.

The VAT head itself can be arranged in any kind of geometry. Results shown here have been obtained with a 3mm diameter cathode wrapped into an alumina tube, which itself was surrounded by a 2mm thick copper tube functioning as the anode.

Measurement of plasma parameters

The essential plasma parameters for determining the performance of the thruster are cathode erosion rate, arc-to-ion current ratio, charge state distribution and velocity of the produced plasma. These parameters have been measured for a variety of materials. The plasma streaming velocity was measured by placing two Faraday cups (FCs) 15 and 20 cm downstream of the arc source. The FCs were negatively biased to collect ions. The velocity is derived from the time delay between the onset of the two Faraday cup signals. The measured plasma streaming velocities are in the range of 1-3 x10^4 m/s as listed in Table 1.

Table 1: Measured arc plasma streaming velocity of several cathode materials.

Element	velocity (10^4 m/s)
Al	2.99
Ti	1.67
Ag	1.25
Ta	1.11
W	1.43

The ion flux (or current) of the arc plasma was measured using biased Faraday cups. The ion charge states and the cathode erosion rates of the arc discharges were measured at Lawrence Berkeley Lab. The ion charge state spectrum is important for deriving the mass flow from the ion current measurements. The composition of the ions was measured using a time-of-flight device, in which a sub-microsecond sample of the ion pulse was drifted down a field-free region and separated into its different charge to mass components. The erosion rates of the cathode material were measured by weighing the cathode material before and after many discharge pulses. Since the total eroded material in the measurements is on the order of several mg, tens of thousands discharge pulses were required. Table 2 lists the preliminary results of the measured ion charge state and cathode erosion rates.

Table 2 Mean ion charge state of vacuum arc plasmas.

Element	Mean ion charge state	Cathode erosion rate (μg/C)
Ti	2	30
Y	2.3	36
Ag	2.14	20
Ta	2.9	58
W	3	60

Estimate of thruster efficiency

It is possible to predict the thruster performance of the VAT using these plasma parameters.

The efficiency of the vacuum arc thruster is given by

$$\eta = \eta_{PPU}\eta_{arc\_energy}\eta_{propellant} \qquad (1)$$

where η_{PPU} is the efficiency of the power processing unit, η_{arc_energy} is the ratio of the plasma energy to the arc energy, and $\eta_{propellant}$ can be obtained from the ratio of the ion flux in the exhaust stream to the total emitted cathode ion flux. As measured in a tungsten arc, the ion streaming velocity, arc voltage (at 30 A), and cathode erosion rate are $1.43\text{x}10^4$ m/s, 30 V, and $60\text{x}10^{-9}$ kg/C, respectively. We have,

$$\eta_{arc\_energy} = \frac{\dot{m}_{arc} v^2}{2 I_{arc} V_{arc}} = 17\% \qquad (2)$$

and

$$\eta_{propellant} = \frac{\dot{m}_{arc}}{\dot{m}_{cathode}} = \frac{0.078 I_{arc}\rho/Q}{\dot{m}_{cathode}} = 83\% \qquad (3)$$

where ρ and Q are the mass and mean charge of tungsten ions (3+), respectively and the ion current is 7.8% of the arc current. Our measurement of 83% W mass utilization rates is less than the ≥95 % reported in the literature, which is perhaps due to the measuring technique of macroparticle mass [11]. As measured from our inductive driver [12] the PPU efficiency can be 92%. Thus, the estimated overall efficiency of the VAT is ≈13%. Recall that the tungsten plasma streaming velocity is $1.4\ \text{x}10^4$ m/s, which implies a thrust/power ratio of ≈18.2 μN/W.

Thrust measurements

The thrust of the VAT was measured at the NASA Jet Propulsion Lab in Pasadena, CA.

Vacuum Facilities at JPL

All the thrust measurements were conducted in a 1.5 m diameter, 2.0 m long steel tank containing a micro-thrust stand. The tank is initially evacuated by a Kinney KMBD-200 blower and backed by a Welch Duo-Seal mechanical pump. For high-vacuum conditions, the tank is isolated from the roughing pumps and a CVI TM500 twenty-inch cryo-pump pumps the tank to an operating pressure of $1\ \text{x}10^{-6}$ Torr.

JPL Micro-thrust Stand

A high resolution micro-Newton-level thrust stand has been built and tested in the Advanced Propulsion Technology facilities at JPL. Following a design used at Princeton [13], the JPL micro-thrust stand is capable of resolving steady-state thrust as low as 10 μN and impulse values as low as 1 μNs with < 10 % error. The impulse is measured by monitoring the position of the thrust arm during the tests. The thrust stand has a vertical rotational axis through two flexural pivots that allows relatively friction-free rotational motion in the horizontal plane. The pivots are located at the center of mass of the thrust arm to reduce the transmittance of low frequency motion perturbations from the vacuum pumps and random facility vibrations. An electromagnetic coil is used to dampen the response of the thrust arm and can be adjusted to produce nearly critical or slightly under-damped conditions. Knowing the position of the thruster at all times during an experiment allows the force to be determined based on calibrated thrust stand dynamics. In the case of very short duration accelerations, as with most pulsed plasma thrusters, the force can be considered impulsive and observing the change in velocity of the effective thruster mass is enough to determine the impulse magnitude.

To determine the velocity change, a damped sinusoid is fit to the position history data before and after the impulse. The physical structure of the thrust stand is shown in Fig. 5.

The thrust stand is calibrated by supplying known impulses to the system along the thrust axis and monitoring the position history. During the calibration procedure, the impulse is supplied by a force transducer mounted at the end of a pendulum. The release of the pendulum and the force transducer impact with the thrust arm is triggered from outside the vacuum tank. The impact pendulum can be set to deliver a wide range of impulse magnitudes by adjusting the pendulum release angle. For each trial, the force from the transducer is recorded on a digital oscilloscope and numerically integrated at the same time as the displacements from the LVDT are recorded. Dividing the impact provided by the force transducer by the velocity change given by the LVDT position history yields the effective mass value for that trial. Typically over twenty trials are used to determine the effective mass within < 2%

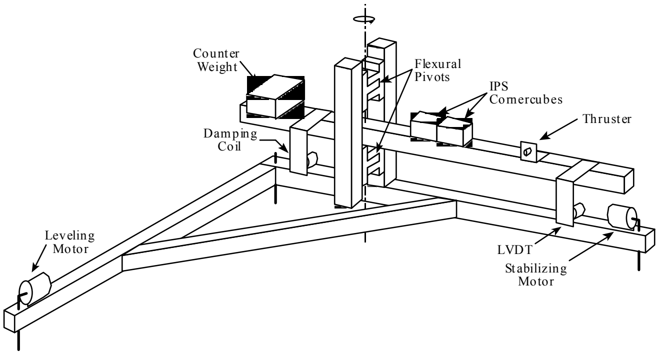

Figure 5: JPL micro-thrust stand.

The VAT was tested at JPL to determine impulse bit and thrust. In the figure above the complete VAT with PPU and thruster head is shown on the left with a total mass of 150g. The input requirements for the version tested include the bus power supply and a 5V trigger to turn the system on and off. In the case of the thrust measurement the internal rep. rate was set to 50Hz and the burst length was varied externally from 20ms (1 pulse) to 1min (3000 pulses). We have tested W and Ti cathodes with an alumina insulator and a copper anode. During one test series up to 60,000 pulses were fired with one single cathode.

Thrust Measurements for Titanium

Measurements were made using Titanium cathodes as well. Not only was the thrust measured but also the power input into the PPU as shown in Figure 6. By doing this we have been able to determine a thrust-to-power ratio that includes all inefficiencies of the plasma source and the power processing unit.

Thrust measurements were made over a wide range of input powers and resulted in an overall ratio of 2.2 μN/W as shown in Figure 7.

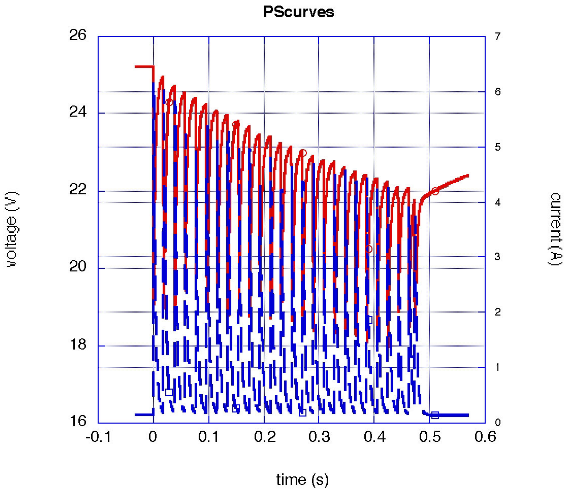

Figure 6: current and voltage output of the power supply at an operating frequency of 50Hz.

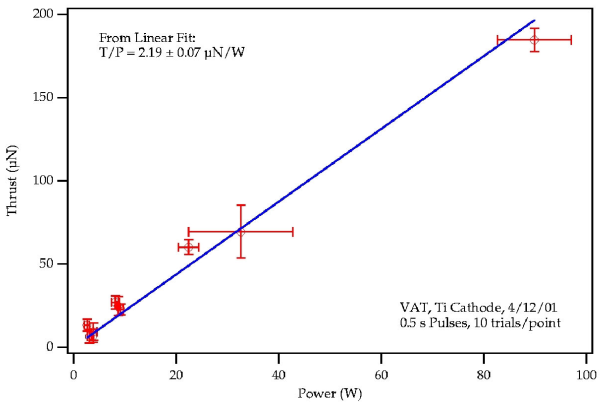

Figure 7: Measured thrust as a function of bus output power.

This value appears to be very small compared with estimated values for tungsten. However titanium is a lighter material. To make an estimate about how much thrust-to-power we should have expected we need the following data:

m = atomic mass Ti=7.97x10^{-26} kg
v = ion Velocity = 1.67x10^{4} m/s
r = ratio Ion current/arc current = 4%
V = Burning voltage = 24.7 V
Q = Mean ion charge = 3.2x10^{-19} C

The thrust is determined by the propellant mass flow rate and the exhaust velocity relative to the vehicle.

The propellant mass flow rate is the flow rate of ions which is determined by:

$$\begin{aligned} \dot{m}_p &= r \cdot I_{arc} \cdot m / Q = 199.2 \mu g / s \\ F &= \dot{m}_p \cdot v = 3.3 mN \end{aligned} \qquad (4,5)$$

for an arc current of 20A.

In order to determine the thrust to power ratio we use the measured arc voltage of 24.7 V. The calculated thrust to power turns out to be:

$$R = F / I_{arc} \bullet V_{arc} = 6.7 \mu N/W \qquad (6)$$

This is still much more than the measured value of 2.2 µN/s.

In order to determine the thrust to bus output power the efficiency of the power processing unit and other loss mechanisms have to be taken into account.

One important loss mechanism is the expansion of the plasma. The above equations assume that all ions leave in a direction normal to the cathode surface. However, earlier experiments at AASC have shown that an expansion angle of 30º is more realistic. This would reduce the thrust from that calculated as discussed by Polk et al. [14].

Another not very well known parameter is the ion to arc current ratio. The value of 4% had been measured at AASC with a slightly recessed cathode. In the thrust measurements the cathode was recessed even more. Tests were made to determine the arc-ion current ratio for different geometries. The results are shown in Figure 8:

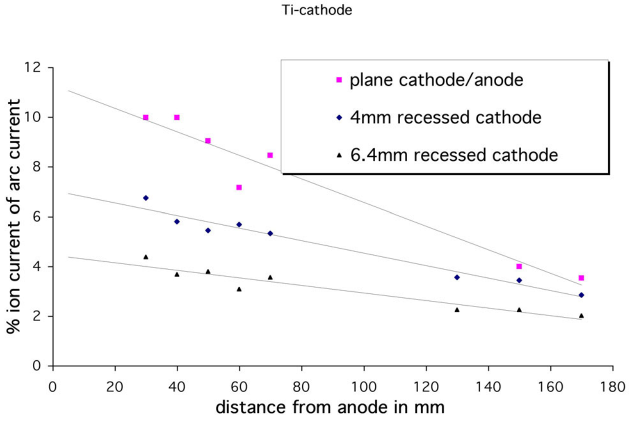

Figure 8: Ion/arc current ratio as a function of thruster geometry.

The ion current was measured with an ion collector at various position downstream of the cathode and extrapolated to the cathode surface. It turned out that for a geometry in which the cathode lies in the same plane as the anode the ratio can be as high as 12% whereas it drops for a 6.4mm recessed cathode to values around 4%. In the tested geometry the cathode was recessed even more due to constant erosion. A ratio of <2% can be assumed for this case, which in turn would correct the estimated thrust/power value to a value very close to the measured one.

With these data the efficiency of the Ti thruster can be calculated. The efficiency of the vacuum arc thruster is estimated by

We have for titanium,

$$\eta_{arc\_energy} = \frac{\dot{m}_p v^2}{2 I_{arc} V_{arc}} = 5.6\% \quad \text{and} \qquad (7)$$

$$\eta_{propellant} = \frac{\dot{m}_P}{\dot{m}_{catthode}} = \frac{0.04 I_{arc}\, m / Q}{\dot{m}_{catthode}} = 33\% \qquad (8)$$

where *m* and *Q* are again the mass and mean charge of the Ti ions, respectively and recall that the ion current is 4% of the arc current for a geometry with a slightly recessed cathode. These estimates are of course independent of the arc current, which is part of the $dm_{cathode}/dt$, too. Including the efficiency of the PPU, the overall efficiency of the Ti thruster is estimated to be 1.6%, which compared to the 13% estimated for tungsten appears to be very small. With the geometry used, the efficiency turned out to be even worse (≈0.6%), which suggests an ion-to-arc current ratio of only 2%. However, taking the geometry factor into account it is obvious that this efficiency can be greatly improved if the ion/arc current ratio can be increased. An increase by a factor of 2 (readily achieved by optimizing the cathode recess) would already provide an overall efficiency of about 7%.

Interpretation and future work

Measurements have shown that the VAT's performance can be predicted by determining the plasma parameters. The thruster has to be designed carefully so as not to unnecessarily obstruct the flow of ions. By optimizing the thruster geometry and using materials heavier than Ti, thrust-to-power ratios of ≈20µN/W will be possible with efficiencies approaching ≈15%.

The VAT has a very small pulse to pulse variation. During one test series up to 60,000 pulses were fired in bursts up to 1 min. The PPU easily regulates the total number of impulses to the next nearest pulse, thereby providing precise impulse control. For example, a pulse-pulse variation of ±10% (1-σ) at 0.1µNs/pulse along with a total number of impulses of 10,000 (1 mNs total impulse) would result in an integrated impulse variation of <±0.1%. This degree of reproducibility and control makes the VAT ideal for precision pointing maneuvers.

Future work includes design of active and passive feed mechanisms to keep the thruster efficiency high with increasing mission duration. Further optimizations include PPU design to minimize leakage current during the off time and recovery of stored energy in the inductor after plasma cut-off.

References

1. J. Mueller, "Thruster Options for Microspacecraft: A Review and Evaluation of state-of-the-art and Emerging Technologies", in 'Micropropulsion for Small Spacecraft', edited by M. M. Micci and A. D. Ketsdever, Progress in Astronautics & Aeronautics, Vol. **187**, p. 45 (2000).
2. R. A. Spores and M. Birkan, "The USAF Electric Propulsion Program", in 35th Joint Propulsion Conf., Los Angeles, CA, 1999. AIAA paper 99-2162.
3. J. Dunning and J. Sankovic, "NASA's Electric Propulsion Program", in 35th Joint Propulsion Conf., Los Angeles, CA, 1999. AIAA-99-2161.
4. D. L. Tilley and R. A. Spores, "Life Extension Strategies for Space Shuttle-deployed Small Satellites Using a Pulsed Plasma Thrusters," 32nd Joint Propulsion Conf., AAIA Paper 96-2730, Lake Buena Vista, FL July 1-3, 1996.
5. Vacuum Arcs - Theory and Applications, edited by J. M. Lafferty (Wiley, New York, 1980).
6. H. C. Miller, " A Bibliography and Author index for Electrical Discharge in Vacuum (1897-1986)", General Electric Co., Document No. GEPP-TIS-366e (UC-13), March 1988; also published in part in IEEE Trans. Elec. Insul. **25**, 765 (1990) and **26**, 949 (1991).
7. R. L. Boxman, P. Martin and D. Sanders, eds., Vacuum Arc Science and Technology, (Noyes, NY, 1995).
8. A. Anders, IEEE Trans. Plasma Sci. 29 (2001) 393-398
9. I. G. Brown, *Rev. Sci. Instrum.* **65** (1994) 3061-3081
10. A. Anders, J. Schein, and N. Qi, , Rev. Sci. Instrum. **71**, 827 (2000).
11. S. Anders, A. Anders, K. M. Yu, X. Y. Yao, and I. G. Brown, IEEE Trans. Plasma Sci. **21** (1993) 440-446.
12. J. Schein et al. *to be published*
13. E.A. Cubbin, J.K. Ziemer, E.Y. Choueiri, and R.G. Jahn, Rev. of Sci. Instrum., 1997, vol. 68(6), pp. 2339-2346
14. J. E. Polk et al. "A Theoretical Analysis of Vacuum Arc Thruster Performance" in 27th IEPC Pasadena, CA, 2001 IEPC-01-211