The vacuum arc ion thruster

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Abstract. The Vacuum Arc Thruster (VAT) is a simple electric propulsion system that produces a pulsed plasma. In this work the VAT is investigated as a plasma source for a gridded ion thruster, the Vacuum Arc Ion Thruster (VAIT). To this end, total ion current measurements were made and the ion to arc current ratio was calculated for three different VATs across two different thruster geometries; planar and coaxial, and cathode materials; steel and bismuth. A maximum ion to arc current ratio of $10.27 \pm 0.5\%$ was obtained from a coaxial thruster firing a steel cathode. It is concluded that the VAT is an ideal plasma source so long as the unique demands of high peak ion current and non-uniform plasma density can be accommodated by an appropriate grid system.

1. Introduction

Gridded ion thrusters operate by accelerating ions from a plasma through a strong electric field, between two or more grids, to very high velocities. These ion thrusters offer some of the highest electrical efficiencies ($60 - 80\%$) and specific impulses ($> 5000s$) of any practical space propulsion system [1]. This makes them ideal for use on deep space missions, as well as for station keeping applications. Gridded ion thrusters are most commonly fueled by noble gases such as xenon or krypton, which are expensive and require mass-intensive gas handling equipment. The vacuum arc thruster, henceforth abbreviated as VAT, on the other hand, is a very simple low efficiency, low specific impulse propulsion system that uses pulsed arcs to ablate a cathode metal into a plasma. Although the VAT trades performance for simplicity it potentially has many advantages as the plasma source for a high performance two stage system: the vacuum arc ion thruster (VAIT). Firstly it is compact and lightweight and overall much simpler compared to gas based plasma sources. Second, it produces a highly ionised plasma with few neutrals which is desirable for an ion thruster. Finally, it can produce beams of heavy metal ions such as bismuth and uranium - which are 60 and 82 percent heavier than xenon respectively, which is simply not practical with other plasma sources. These higher ion masses mean greater thrust levels are attainable for the same beam current level. As grid erosion is determined ultimately by the beam current, this means a vacuum arc ion thruster could potentially have longer grid lifetimes than gas based systems [5]. In this work we investigate this possibility. The basic space propulsion figures of merit for a vacuum arc ion thruster are presented. This is followed by ion current measurement results from three different vacuum arc thrusters. Finally we discuss these results and outline potential challenges of using the VAT as a plasma source.

2. Vacuum arc ion thruster figures of merit

In a VAIT, the beam current is the total ion current from the VAT that can be extracted by the grid system. The ion to arc current ratio or ion fraction, f_i, is simply:

$$f_i = \frac{J_i}{J_d} \tag{1}$$

Where J_d is the arc discharge current and J_i is the total ion current. The ion mass flow rate is dependent on the ion to arc current ratio, f_i, the ion mass M_i and the average ion charge state $\langle Z \rangle$, where e is the electron charge.

$$\frac{dm_i}{dt} = \frac{M_i f_i J_d}{e} \langle Z^{-1} \rangle \tag{2}$$

The ion current from a VAT is not uniform and has a exponential distribution. Thus a correction factor, C_j, is applied to take this into account. The effective grid transparency is given by ϕ_g. Therefore the ion beam current, J_b, is:

$$J_b = f_i J_d C_j \phi_g \tag{3}$$

The ion velocity, u_i, can then be derived from conservation of energy:

$$\frac{1}{2} M_i u_i^2 = e V_b \langle Z \rangle \tag{4}$$

$$u_i = \sqrt{\frac{2e\langle Z \rangle V_b}{M_i}} \tag{5}$$

Writing the ion beam mass flow rate:

$$\frac{dm_{ib}}{dt} = \frac{dm_i}{dt} \phi_g C_j = \frac{f_i J_d C_j \phi_g M_i}{e} \langle Z^{-1} \rangle \tag{6}$$

The thrust is simply:

$$T = \frac{dm_{ib}}{dt} u_i = f_i J_d C_j \phi_g \sqrt{\frac{2 M_i V_b}{e}} \langle Z^{-\frac{1}{2}} \rangle \tag{7}$$

and the specific impulse:

$$I_{sp} = \frac{T}{\frac{dm_t}{dt} g} = \frac{f_i C_j \phi_g \langle Z^{-\frac{1}{2}} \rangle}{E_r g} \sqrt{\frac{2 M_i V_b}{e}} \tag{8}$$

Where E_r is the VAT cathode erosion rate expressed in $\frac{kg}{C}$ [3].

3. Total Ion Current Measurements

A large collector was used to completely encapsulate the VAT so that ions could be captured from all angles surrounding the thruster, including from behind the thruster. Three different thrusters were tested, a coaxial thruster with a bismuth cathode (99.9% Bi), a coaxial thruster with a mild steel (99.6% Fe) cathode and a planar thruster with a mild steel cathode. The coaxial thrusters had cylindrical cathodes 6.25mm in diameter and an alumina ceramic ($Al2O3$) tubular insulator 3mm thick. The coaxial thruster anodes were copper. The planar thruster had a 1mm flat borosilicate glass insulator separating the anode and cathode which were both

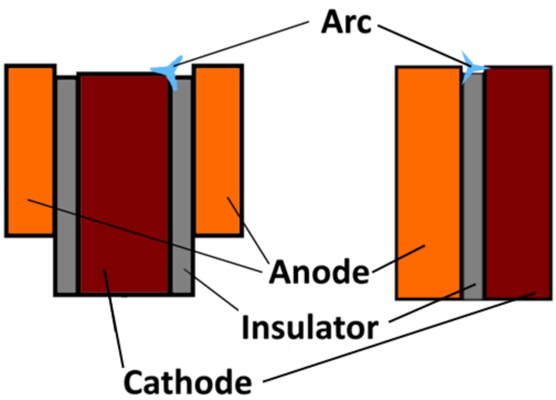

Figure 1. Cross section showing the simple geometry of coaxial (left) and planar (right) thrusters.

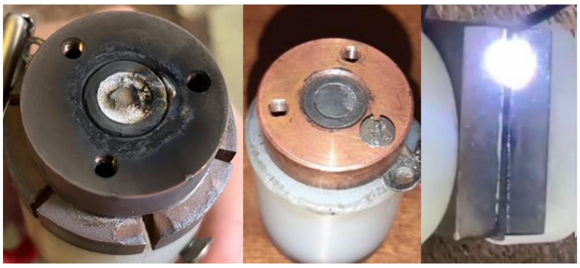

Figure 2. The three VATs used in this work. Left to right: Bismuth coaxial thruster showing clear cathode erosion, coaxial steel thruster with minor erosion and planar steel thruster during arc operation.

mild steel pieces 20mmx5mmx10mm. The planar glass insulator was recessed by 1mm allowing the cathode direct view of the anode. The coaxial thrusters had no recession and the surfaces of the cathode insulator and anode were all in the same plane. A cross section of the geometry is shown in figure 1 and the thrusters are shown in figure 2. All thrusters were driven by the same circuit which relied on an inductive high voltage spike to initiate the arc [2]. Experiments were conducted at $1.5 \pm 0.5 \times 10^{-6}$ Torr. A 0.1Ω resistor was used to measure the ion current, this low value was chosen to prevent a large voltage drop across the collector which could prevent proper repulsion of plasma electrons. The maximum voltage drop the collector would have experienced is $V = IR = 4 \times 0.1 = 0.4V$, which should have a negligible impact on electron repulsion. The circuit drive voltage, which is also the anode voltage relative to the cathode, was $48V$. In typical VAT drive circuits, the arc energy predominantly comes either from a capacitor or an inductor which leads to a very sharp triangular arc pulse shape [6]. This is undesirable for a plasma source as this arc current shape will produce a highly non-uniform ion current. Thus the circuit used in this work was tuned to better match the impedance of the arc plasma, and operates as a one stage Rayleigh type pulse forming network producing roughly square shaped arc current pulses. In all tests the cathode was grounded and the ion collector plate was biased negative relative to ground to reflect electrons from the plasma plume. The negative bias on the collector plate was varied from -0.8V to -60V. Due to the fact that each arc modifies the cathode surface meaning no two arcs are the same, all results presented were averaged over 20 arc pulses.

4. Results

4.1. General findings

The averaged arc and ion currents are shown in figures 3, 4 and 5, where the legend denotes the negative bias voltage on the ion collector. The time has been zeroed to the start of the arc pulse. The arc burns until the current drops below the minimum threshold necessary to sustain the arc, the arc chopping current. As bismuth has a lower discharge voltage than iron, it can sustain the arc for longer before reaching the chopping current. This is clearly seen by the difference in arc length in figures 3 and 4. The coaxial bismuth arcs lasted approximately $1500\mu s$ while the coaxial steel arcs lasted only $750\mu s$. It is interesting to note that the planar steel thruster arcs also lasted $1500\mu s$ despite having the same cathode material as the coaxial steel thruster. This may be due to the fact that the planar geometry, with a 1mm insulator was able to lower the arc chopping current and thus prolong the arc.

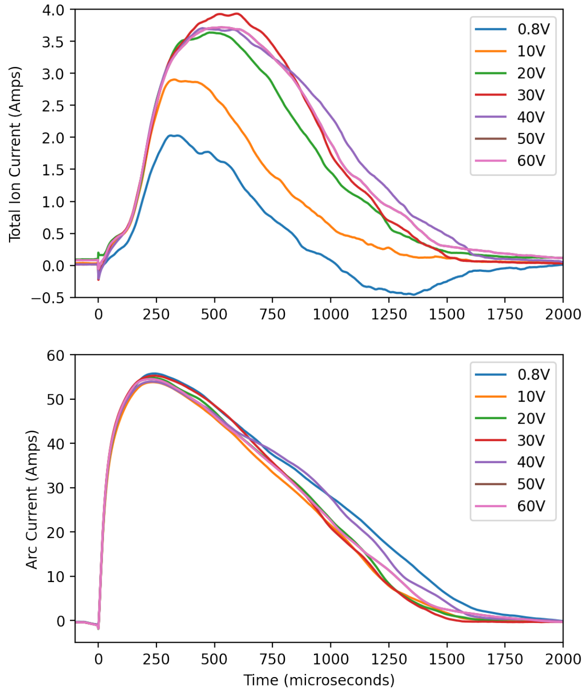

Figure 3. Coaxial bismuth thruster ion and arc currents over the range of ion collector negative bias voltages tested.

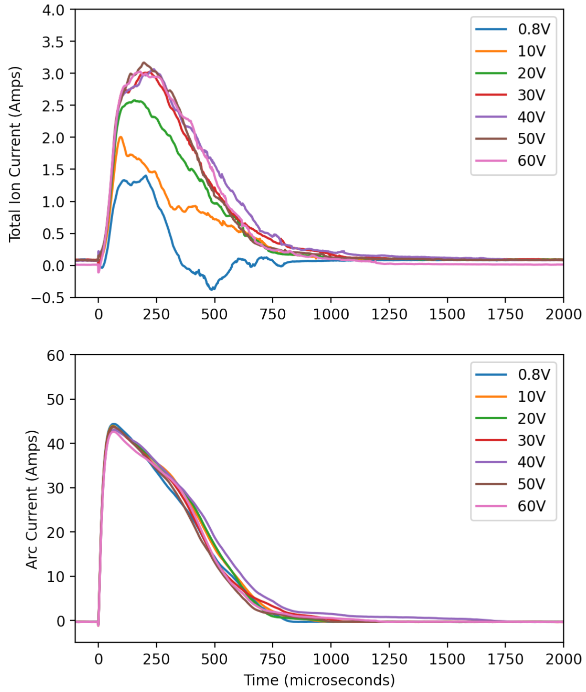

Figure 4. Coaxial steel thruster ion and arc currents over the range of ion collector negative bias voltages tested.

4.2. Ion to arc current ratios

Figure 6 shows the ion to arc current ratio expressed as a percentage of the arc current for all three thrusters. As bismuth has a much lower cohesive energy than iron, it was expected that the coaxial bismuth thruster would produce the highest ion to arc current ratio [4]. However, it was the coaxial steel thruster that had the highest ratio measured at $10.27 \pm 0.5\%$, followed by the bismuth thruster at$7.5 \pm 0.5\%$ and finally the planar steel thruster at $6.73 \pm 0.5\%$.

4.3. Estimation of the plasma electron temperature

The electron temperature in vacuum arc plasmas is known to be on the order of 1 eV [4]. Figure 6 clearly shows a plateau in the ion to arc current ratio as the negative bias is increased beyond -20V. This suggests that the electron temperature is indeed low in all three thrusters regardless of geometry or cathode material.

During the planar steel thruster ion current measurements, there was an issue with the power supply limiting the current. These results were excluded and new tests were repeated with the same supply used for the coaxial thruster tests but at higher voltages. Unfortunately this lead to a lack of data points over the range 20-40V, however the trend of ion current saturation does still appear if somewhat less robustly.

5. Potential drawbacks of the VAT plasma source

The VAT produces a large ion current pulse of several amps. This places a high peak power demand on the accelerator supply; some 6kW peak power assuming 4A beam current and 1500V acceleration voltage. Alternatively a capacitor bank could be used but must be oversized to prevent significant voltage sag during the pulse. Furthermore the grid area would need to be large enough to accommodate this peak ion current. Another challenge to consider is that the

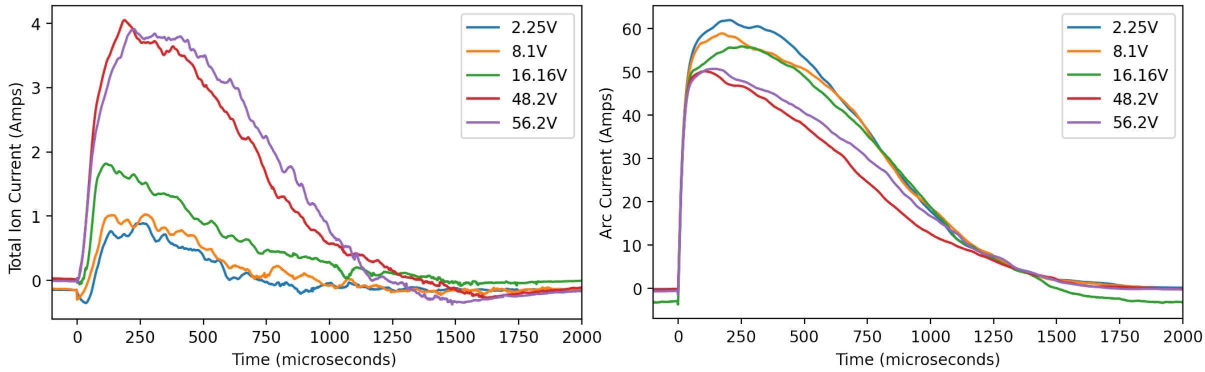

Figure 5. Planar steel thruster ion and arc currents over the range of ion collector negative bias voltages tested.

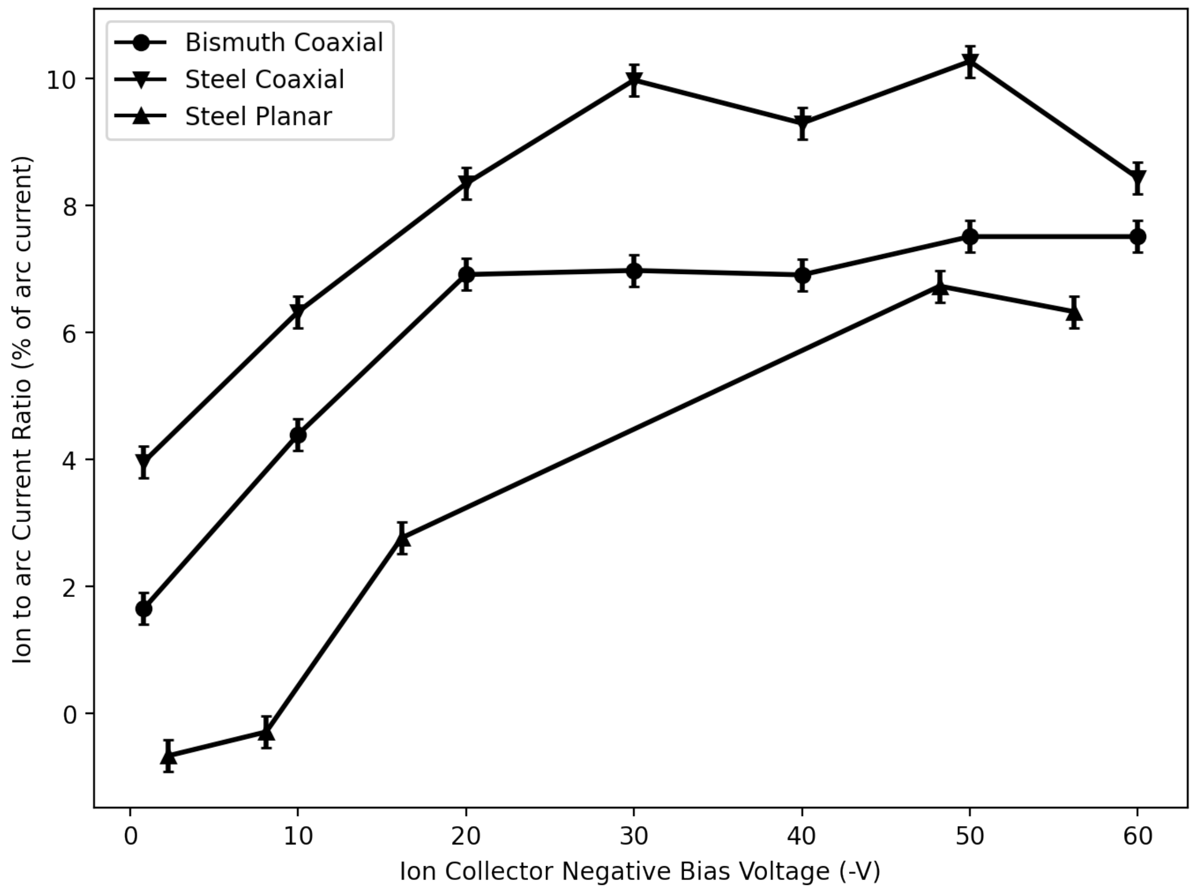

Figure 6. Ion to arc current ratio versus ion collector negative bias voltage, expressed as a percentage of the arc current.

plasma from the VAT is has an exponential distribution; with $_j$ 0.67 as the plume divergence parameter. This means that even if the grid system is capable of extracting the total ion current from the VAT, the space charge limit may be exceeded along the cathode axis. Finally, as the pulse length of the vacuum arc is quite short, in this work some 1-1.5ms; the processes of extraction, acceleration and neutralisation must occur and reach equilibrium very quickly. This situation could be improved by increasing the arc pulse lengths, so long as the cathode can be kept below melting point.

6. Conclusion

In conclusion, the vacuum arc thruster was examined as the plasma source for a gridded ion thruster. The relevant spacecraft figures of merit were presented. Total ion currents were measured for three different VATs by encapsulating them in a large negatively biased ion collector and the ion to arc current ratio f_i was calculated. All thrusters produced ion currents of several amps and ion to arc current ratios above 6%. The coaxial steel thruster produced the highest f_i of $10.27 \pm 0.5\%$. Differences in arc currents, arc burning lengths and ion currents were observed and reasons for these discrepancies discussed. The ion currents began to saturate at -20V bias voltage which implies a low electron temperature in the vacuum arc plasma. These findings show that the VAT can readily produce several amps of metal ions, largely independent of thruster geometry or cathode material. The VAT may be an ideal plasma source if the burdens of high peak ion currents non-uniform plasma density can be overcome.

Acknowledgments

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