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ABSTRACT: A Metal Plasma Ion Thruster (MPIT) uses an ion optics grid structure to accelerate metal ions from a Cathodic Arc source [1] to high speeds. Such a source has earlier [2,3] been published and commercialized as a Metal Plasma Thruster (MPT). Candidate MPIT sources ranging from Mg up to Bi, and include Cu, Zn, Mo, Ag, Cd, In, Sn, W, and Pt. The innovation of this thruster is to take slower moving ions from the cathodic arc source and accelerate them to much higher speeds in the optic grids. The specific impulse (ISP) of the thruster ranges from ~ 3900 s (Bi ions) to $\sim 10,300$ s (Mg ions). The older MPT thruster has a Thrust/Power (T/P) ratio of 11 mN/kW (for Mo propellant), a thrust of 5.5 mN at 500 W at an ISP of 1774 s and an efficiency of $\sim 10\%$. This thrust is well below that at similar ISP from Xe ion engines or Hall Effect Thrusters (HET) operating at similar power. The new MPIT described here offers thrust comparable to the HET but at much higher ISP. The high ISP combined with much higher propellant storage density, makes the MPIT a more compact propulsion system with no moving parts, with a thrust efficiency of $\approx 50\%$. As a complement to Air Breathing Electric

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Propulsion (ABEP) in VLEO or to HETs in LEO, the MPIT introduces a competitive solution for CubeSats and small satellites.

Nomenclature

ISP = Specific Impulse (s)

T/P = thrust/power ratio (mN/kW)

I_{tot} = Total Impulse (Ns)

I_{bit} = impulse bit (mNs)

ΔV = velocity increment (m/s)

$I-U$ = 100 mm x 100mm x 100 mm (CubeSat standard volume)

η_{thrust} = thrust conversion efficiency

P_{screen}^{mps} = Power to screen grid in the ion optics from the metal plasma source

T_{screen} = Temperature of the screen grid in the ion optics

$A_{eff.}$ = Effective radiating area of the screen grid and decel grid in the ion optics

P_{ions}^{mps} = Power to screen from ions ejected by the metal plasma source

$P_{rad.}^{mps}$ = Power into screen from radiation in the metal plasma source

$\langle I_{mps} \rangle$ = Average ion current from the pulsed metal plasma source

$\dot{m}_{mps}$ = mass flow rate from the metal plasma source

$\dot{m}_{ion\ beam}^{grid}$ = mass flow rate of ions in the optics grid

I_{beam}^{grid} = Ion beam current in the optics grids

Z_{beam} = Mean charge of ions from the metal plasma source and in the grids

ϵ_{mps} = erosion rate from the metal plasma cathode

ϵ_o = permittivity of free space

σ = Stefan-Boltzmann constant

U_{mps} = ion speed in the metal plasma source

f = ion fraction in the metal plasma source

M = Atomic mass of metal plasma ions

V_{beam} = Net accelerating voltage between screen grid and accel. grid in ion optics

ΔE_{mps} = Energy into metal plasma arc on each pulse

I_{beam}^{C-L} = Child-Lanmuir saturation ion beam current in optics grids

A_{grid} = transmitting area of screen grid in ion optics

l_e = effective gap between accel. grid and plasma meniscus in screen grid

V_o = Initial voltage on capacitor of metal plasma source

V_F = final voltage on capacitor of metal plasma source

R = pulse repetition rate of the metal plasma source

$v_{ion beam}^{grid}$ = speed of ions exiting the optics grids

$ISP_{ion beam}^{grid}$ = Specific Impulse of ions exiting the optics grids

1 Background of the invention

This paper describes a new type of ion thruster that uses a solid metal plasma as its ion source. Traditional ion engines [4,5] use noble gases such as Xe as propellant. They also ionize and accelerate the Xe ions using a single power supply. A consequence of this is that for a fixed input power, there is an inverse relationship between thrust and specific impulse or ion speed. The specific impulse ISP is a measure of the thrust that is produced per unit of fuel expended per unit time and is a measure of the fuel efficiency of the system. Mathematically, the specific impulse is defined as the exhaust velocity of the thruster divided by the acceleration due to gravity at the surface of the earth, g . Higher ISP means less fuel used for a given mission ΔV . ΔV , also called

Delta-vee, is the change in velocity required for any orbital maneuver. For example, to change an orbit from 500 km to say, 975 km, then revert to 500 km using a Hohmann transfer requires a DV of ≈ 500 m/s.

The new ion engine described in this paper, dubbed the Metal Plasma Ion Thruster (MPIT), gives thrust that is comparable to thrust from similarly powered gridded ion engines or Hall Effect Thrusters (HETs), but at higher ISP. The higher ISP reduces the propellant consumption and hence the volume of the thruster. Use of solid metal at much higher density: 7 kg/m^3 (Zn) – 21.45 kg/m^3 (Pt), versus 1.6 kg/m^3 for Xe in Ion engines or HETs, further reduces the thruster volume. No tanks are required, nor plumbing, valves or controls.

2 MPIT derives from the Metal Plasma Thruster (MPT)

The MPIT combines two already matured technologies:

The Metal Plasma Thruster (MPT) [2] which has no moving parts, stores fuel as a dense solid and provides thrust by ionizing a small quantity of solid metal and ejecting it in short pulses into space at high velocity. Each pulse typically ionizes tens of micrograms of metal and ejects it at speeds ranging from ~ 4733 m/s (Bi propellant) up to $19,836$ m/s (Mg propellant). The corresponding Specific Impulse (ISP) values range from 483 s (Bi) up to 2022 s (Mg). *But the MPIT does not rely upon this ejected plasma for thrust.* It merely uses the plasma as a source of ions that are then accelerated to much higher speeds, to generate higher thrust. Consequently, the MPIT does require an electron neutralizer, but such neutralizers are mature technologies developed over several decades for ion engines and HETs.

A gridded accelerator structure that extracts ions from the metal plasma and accelerates them to much higher speeds than in the native metal plasma. The corresponding ISP values range from 3881 s (Bi) up to $10,294$ s (Mg). The Bi ISP is 7 times higher than in the native MPT thruster. The

Mg ISP is 5 times higher. These are huge differences. For example, consider a 150 kg satellite that requires 1000 m/s ΔV for some orbital maneuver. As shown in a later section, the MPIT offers thrust that is comparable to that of the HET (at the same ISP) but due to its higher storage density delivers the same total impulse in a much smaller volume. Table 1 shows (using the rocket equation), that the propellant mass and volume required are 6.5 times smaller for the MPIT operating with Bi than for the MPT. The propellant mass required for the same 150 kNs total impulse maneuver using an HET is three times that required by the MPIT; the storage volume is 17 times larger.

150 kg SAT; $\Delta V=1000$ m/s, TOT IMP 150 kNs

Thruster	ISP, s	Prop.mass, kg	VOL., L
MPT	483	28.5	2.91
MPIT (Bi)	3457	4.4	0.44
HET (Busek)	1244	11.8	7.38

Table 1: Propellant mass and volume required for a 1000 m/s DV maneuver: MPIT v. MPT and HET

The MPIT is a new ion thruster that competes with Xe ion engines and HETs, with greater efficiency, more compact system volume and greater simplicity.

Several published papers [2,3] describe the performance of the MPT thrusters. The thrust from an MPT is lower than the ideal value (mass flow rate of propellant x exhaust speed) due to three deleterious factors:

1. The plasma plume ejected from the propellant surface does not flow purely normal to the propellant surface but expands into a “supersonic” cone, somewhat like a $\cos^M(\theta)$ distribution, where M is the effective supersonic Mach number (directed axial speed divided by the random thermal speed) of the expanding plasma plume. The typical angle of this cone within which is contained 90% of the flux is $\pm 50^\circ$, so that there is a radial component of momentum that does not contribute to thrust. Taking the plasma flux

profile and this supersonic expansion into account, the axial thrust is reduced by $\approx 17\%$ for a $\text{Cos}^4(\theta)$ distribution.

2. The plasma produced at the propellant surface is not fully ionized. The degree of ionization varies from a low of 60% - 70% for soft metals such as Bi, Li, Mg etc. to 90% to nearly 100% for refractory metals such as Nb, Mo or W.

3. The anode of the arc discharge that creates the plasma plume intercepts a small fraction of the expanding plasma, typically 5% - 10%.

These deleterious losses reduce the effective axial thrust to between 50% (soft metals) to 75% (refractory metals) of the theoretical maximum value.

Measurements made on a sensitive pendulum thrust stand at NASA Glenn Research Center and published[3] showed that the correction to ideal thrust was around 65% - 70% for Mo propellant, which corroborated the above analysis. In practical terms, the Thrust/Power ratio (T/P) of the MPT varies from a low of 6.1 mN/kW (for W) up to 13.2 mN/kW (for Ag). Mo was measured to give 11 mN/kW on the NASA thrust stand.

Table 2 lists different MPT propellants, their ISP and the Thrust/Power ratio, benchmarked against the measured value of 11 mN/kW for Mo. The ISP values are obtained from published [1,6-8] literature on vacuum arcs over several decades of research from the 1970s to the present. The last column in the table shows calculated T/P ratios for a Busek BT-350 Hall Thruster. The published T/P ratios for the Hall thruster have been adjusted for the ISP values of the various MPT propellants. For example, the Busek HET is quoted at 49 mN/kW at an ISP of 1244s. To compare it with the MPT operating with Mo at 1775s, the ratio is adjusted downwards by the factor (1244/1775) to 34.1 mN/kW, since the T/P ratio generally shows an inverse relationship with ISP.

Propellant	ISP, s	T/P ratio, mN/kW	T/P ratio of Busek BT-350
Mg	2022	10.0	28.8
Cu	1349	7.3	43.2
Zn	1056	9.0	55.2
Mo	1775	11.1	32.8
Ag	1139	13.2	51.2
Cd	698	10.0	83.5
In	599	7.9	97.3
Sn	716	10.2	81.4
W	1136	6.1	51.3
Bi	483	13.6	120.8

Table 2: MPT propellants, ISP and Thrust/Power ratios, with Busek Hall Effect Thruster for comparison

The table shows that the MPT delivers T/P ratios that are 3x to 12x lower than for the HET at the same ISP operating points. Note that the HET does not necessarily operate well at all these ISP values, yet the comparison is made as if it could operate over the whole range. If one compares the MPT to a gridded ion engine at typical ISP of 2000s, the T/P ratio of a Xe ion thruster is ~ 30 mN/kW – 40mN/kW, which is still 3x – 4x higher than that of the MPT at similar ISP. So, the MPT gives ≈ 11 mN/kW, the gridded ion engine ≈ 35 mN/kW and the HET ≈ 33 mN/kW at ISP values around 1775 s. The T/P ratio of the MPT is lower than that of ion engines or HETs.

The MPIT overcomes this deficit of the MPT, while increasing its efficiency.

The main advantage of the MPT (despite its lower T/P ratio) over HETs or gridded ion engines is that the propellant is stored at solid density, ranging up to 21.5 kg/L for Pt, versus 1.6 kg/L for Xe in the HET or gridded ion engines. If the satellite has limited volume for propulsion, the MPT offers an advantage over Xe Hall thrusters. But larger satellites (>150 kg mass) that can accept the larger volume requirement of the HET would prefer the HET, for its significantly higher T/P ratio. This comparison of the MPT with HETs and gridded ion engines appears to indicate that the MPT is most advantageous for CubeSats with mass <150 kg, where minimizing the volume and mass of the thruster is of importance to the mission planner. But what if there is a way to overcome the

low T/P ratio of the MPT while retaining its advantages of dense solid fuel, no moving parts, gases or valves or standby heaters? *That is what the MPIT accomplishes.*

The Metal Plasma Ion Thruster (MPIT) uses the MPT discharge as merely a source of highly ionized metal plasma that impinges upon a screen grid. This screen grid is part of a gridded ion beam accelerator that extracts metal ions from the MPT plasma plume, post-accelerates them to much higher speeds than in the native MPT plume, to provide a higher thrust, more efficient and higher total impulse thruster. When compared to a HET or gridded ion engines, the MPIT is shown capable of higher thrust at higher ISP than both engines, with comparable Thrust/Power ratio.

The rest of this paper describes the invention. Section 3 describes the MPIT structure and presents its operational capability as compared with a similar powered HET. Section 4 presents a detailed analysis of the MPIT from first principles, first using Bi propellant as an example. Many other candidate propellants are also analyzed. Section 5 presents candidate designs using several propellants. Section 6 examines grid contamination which could be the practical limitation of such metal thrusters. It is shown that Zn is a particularly good choice to overcome grid contamination in a thruster that delivers > 150 kNs from a <10 kg mass and <3 L volume. Section 7 is a summary, followed by acknowledgements and references.

3 Structure and operating principle of the MPIT

Figure 1 shows a schematic drawing of the Metal Plasma Ion Thruster (MPIT). The PPU has two components: 1. The low voltage (45 V max.) PPU of the existing MPT, a flight-ready unit, 19 of which have been launched into LEO since 2024; 2. A separate PPU (~ 1 kV max.) for the gridded ion optics, such as PPUs that have been used in gridded ion engines for >50 years. The MPT cathode and coaxial anode are floated relative to spacecraft potential, as shown in the potential profile in the lower part of the figure. When the MPT is fired, a metal plasma plume is launched

from the cathode 106 past the hollow anode 120 and onto the screen grid 404, with $\approx 95\%$ passing beyond the anode. This section of the MPIT is identical to the MPT, as it serves to create a metal plasma plume.

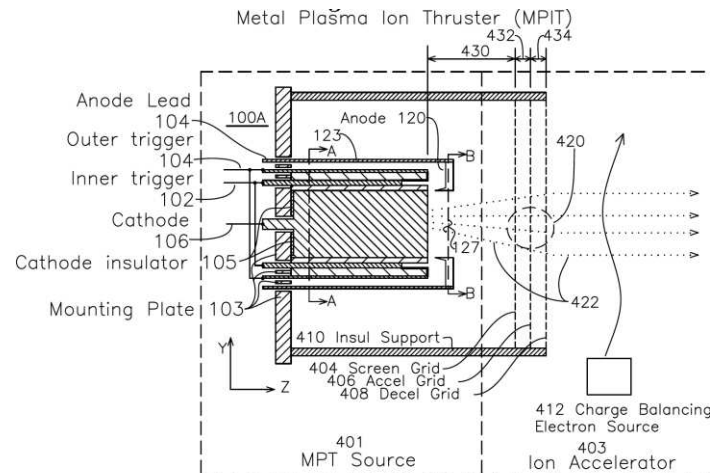


Figure 1: Outline drawing of Metal Plasma Ion Thruster (MPIT)

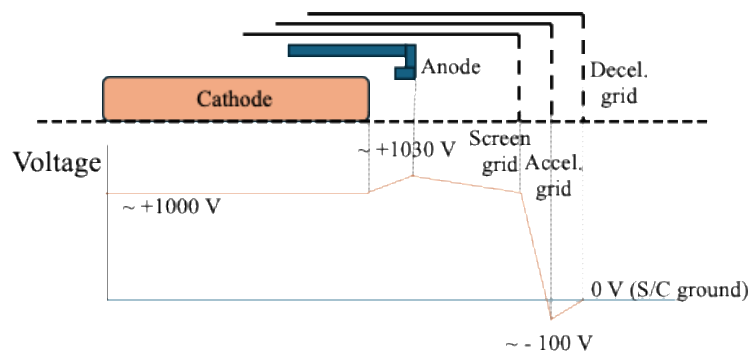


Figure 2: Potentials at various locations of the MPIT

Figure 2 shows the potentials at various locations of the MPIT. The metal plume impinges upon a screen grid that is held at the same potential (~ 1000 V) as the cathode. The ring anode is biased positively relative to the cathode/screen. Its initial voltage is $+45$ V relative to the cathode/screen. During the few ms arc discharge, this voltage drops to the “burning voltage” of the arc, shown in the figure as $\sim +30$ V, but varying from $+15$ V for softer metals up to $+32$ V for refractory tungsten. Beyond the screen grid is an acceleration grid that is at -100 V relative to space craft (S/C) potential. This accel. grid is followed by a decel. grid that is close to or at spacecraft potential.

The role of the accel.-decel. arrangement is to prevent electrons injected by the neutralizer into the exhaust plume from flowing back into the arc discharge region, gaining ~1000 eV and impinging upon the anode to damage it. Such an accel.-decel. arrangement is almost always used in gridded ion engines and dates to the 1960's.

How is this MPIT better than the MPT?

Firstly, to provide a baseline, suppose that the screen grid transmits 65% of the incident ion flux from the plasma plume? The open area of only 65% ensures mechanical rigidity of the grids (like what is used in gridded ion engines). If this flux is accelerated to the same speed as the incident plasma ions, the thrust would be the same as for the MPT alone. This is because the MPT alone, as discussed earlier, loses 25% to 50% of thrust (average across all metals is 35%) due to deleterious factors. The gridded optics produce a fully collimated ion beam whose thrust has no off-axis vectors.

Secondly, the point of the MPIT is not to merely match the speed of the incident ions, but to accelerate them. If the speed is tripled by the optics, then thrust is also tripled, with the additional benefit of a higher ISP. The higher ISP implies lower propellant mass required for a given ΔV , leading to a much more efficient thruster.

The next section derives equations that characterize the operation of the MPIT. Such a first principles analysis of the arc discharge physics and the grid optics enables a head-head comparison of the MPIT with HETs or Ion Engines.

4 Derivation of thrust, Specific Impulse, efficiency and total impulse of the MPIT

With reference to Figure 1, for a specified grid accel. voltage V_b , the Child-Langmuir saturated ion I_{beam} current I_{beam} is given by:

$$I_{beam}^{C-L} = \left(\frac{4\epsilon_0}{9} \right) \sqrt{\frac{2Z_{beam}e}{M}} \frac{V_{beam}^{1.5} A_{grid}}{l_e^2} \quad (1)$$

The open grid area is only 65% of the geometric area as shown in Eq. 2.

$$A_{grid} = 0.65 * \pi * \frac{D_{screen}^2}{4} \quad (2)$$

The Child-Langmuir beam current I_{beam}^{C-L} (or I_{beam}^{grid}) is related to the ion mass flow rate inside the diode $\dot{m}_{ion beam}^{grid}$, shown in Eq. 3.

$$\dot{m}_{ion beam}^{grid} = \frac{M * I_{beam}^{grid}}{Z_{beam} * e} \quad (3)$$

Next, we impose a continuity requirement, viz:

$$0.65 * \dot{m}_{screen}^{mps} = \dot{m}_{ion beam}^{grid} = \frac{M * I_{beam}^{grid}}{Z_{beam} * e} \quad (4)$$

Eq. 3 states that since the screen is 65% open, then 65% of the mass flow of ions from the arc must equal the mass flow of ions out of the decel grid. Otherwise, mass will pile up on the screen or the grids will be starved of sufficient mass to satisfy the Child-Langmuir diode current. The mass flow rate of ions to the screen is related to the mass flow rate $\epsilon_{mps} * \langle I_{mps} \rangle$ out of the propellant cathode, as shown in Eq. 4, where ϵ_{mps} is the erosion rate of the propellant, a quantity that has been measured for almost every conducting element by several authors, notably Anders [1] and Brown [9], by the transmission (or open area) of the mps anode, which is 95% for this study.

$$\dot{m}_{screen}^{mps} = \epsilon_{mps} * \langle I_{mps} \rangle * f * 0.95 \quad (5)$$

Eqs. 4 and 5 give the ion current inside the diode grids:

$$I_{beam}^{grid} = \frac{0.65 * Z_{beam} * e * \epsilon_{mps} * f * 0.95 * \langle I_{mps} \rangle}{M} \quad (6)$$

But for continuity, this ion current must equal the current driven by the accel. voltage inside the grids, which is the Child-Langmuir saturation current, given by Eq. 1.

To estimate the power onto the screen, begin by estimating the power due to the streaming ions that impinge upon the grid from the arc discharge plasma, henceforth referred to as the Metal Plasma Source, or mps in the equations.

$$P_{ions}^{mps} = \dot{m}_{mps} * f * \frac{U_{mps}^2}{2} = \varepsilon_{mps} * \langle I_{mps} \rangle * f * \frac{U_{mps}^2}{2} \quad (7)$$

Eq. 7 shows that this ion beam power is given by half the product of the mass flow rate $\dot{m}_{mps}$ from the arc discharge times the square of the ion speed, U_{mps} . The factor f is the ion fraction. As stated earlier, this fraction varies from 63% up to 100% in cathodic arcs, depending on how refractory is the cathode material. The mass flow rate from the cathodic arc is given by

$\varepsilon_{mps} * \langle I_{mps} \rangle$, where ε_{mps} is the erosion rate from the cathode and $\langle I_{mps} \rangle$ is the average arc current of the pulsed arc. In addition to the streaming kinetic energy of the ions, the screen is also heated by radiation from the hot plasma. It is not easy to estimate this source of screen heating, as the plasma is an optically thin, line radiation source with spectral emission lines from several charge states of the cathode atoms as well as a Bremsstrahlung continuum. One way to bound this estimate is by an energy balance. The energy input to the arc is partitioned into ionization energy, thermal energy (enthalpy), streaming kinetic energy, Ohmic dissipation in the arc, and radiation. The streaming kinetic energy in such cathodic arcs is typically ~10% of the total energy. We assume that radiation would also be roughly 10%, with the remainder going to the other energy sinks in the discharge. The screen subtends a solid angle to the expanding conical plasma so receives only a fraction of the total radiation. Since the screen is close to the cathode, we approximate the radiation received as being 50% of the total radiation, hence 50% of the ion kinetic power. Hence, the total power into the screen is approximated by Eq. 7.

$$P_{screen}^{mps} = P_{ions}^{mps} + P_{rad}^{mps} \approx 1.5 * P_{ions}^{mps} \quad (8)$$

Eq. 8 with $\langle I_{mps} \rangle$ gives the total power to the screen, called $P_{screen\ TOT}$ in the table, which is also P_{screen}^{mps} from Eqs. 7 and 8.

The power P_{screen}^{mps} impinging upon the screen, that is due to the ion flux from the arc discharge as well as radiation from the plasma, is related to the screen temperature T_{screen} by Eq. 9. Assume that

the screen and other grids are thermally insulated from the thruster body and the spacecraft. The reason for this will become obvious later.

$$P_{screen}^{mps} = \epsilon \sigma A_{eff} T_{screen}^4 \quad (9)$$

σ and ϵ are the Stefan-Boltzmann constants and A_{eff} is the effective radiating area of the screen. To estimate this (Eq. 9), we note that due to the proximity of the screen, accel. and decel. grids (see Figure 1) they will reach an equilibrium temperature although the heating power is incident only upon the screen grid. The screen, accel. and decel grids have an open area of 65% (chosen to ensure mechanical rigidity of the optics, as is typical for ion thrusters). So only 35% of the area radiates and since the screen and decel. grids both radiate heat, we use the factor of 2 in Eq. 9. D_{screen} is the diameter of the screen grid.

$$A_{eff} = 2 * 0.35 * \pi \frac{D_{screen}^2}{4} \quad (10)$$

Eqs. 8 and 9 give the screen temperature, T_{screen} . The reason for calculating the screen temperature (for a thermally insulated optics grid set) is made clearer in a later section where we discuss contamination of the screen grid.

The power into the cathodic arc is given by the energy from the storage capacitor and the pulse repetition rate, R:

$$P_{arc}^{mps} = \Delta E_{mps} * R = \frac{C(V_o^2 - V_F^2) * R}{2} = \frac{(V_o + V_F)}{2} * C * R * (V_o - V_F) \quad (11)$$

Since $C * R * (V_o - V_f)$ is the average current $\langle I_{mps} \rangle$:

$$P_{arc}^{mps} = \frac{(V_o + V_F) * \langle I_{mps} \rangle}{2} \quad (12)$$

$$P_{TOTAL} = P_{mpit} + P_{arc}^{mps} \quad (13)$$

Eq. 13 is the total power into the MPIT. Since this is often limited by the available power for propulsion on small satellites, this power is set to some maximum and fixed value such as 500 W, in what follows.

$$v_{ion\ beam}^{grid} = \sqrt{\frac{Z_b e V_b}{M}} \quad (14)$$

Eq. 13 gives the exhaust ion beam velocity, $v_{ion\ beam}^{grid}$ from the derived voltage V_b . The ISP is given by Eq. 14.

$$ISP_{ion\ beam}^{grid} = \frac{v_{ion\ beam}^{grid}}{g} \quad (15)$$

Eqs. 1 – 15 constitute a complete set derived from first principles, from which the performance of the MPIT may be evaluated for different constraints. The next section presents a few candidate designs.

5 Candidate designs

Consider the case for which the total input power to the two PPU's is fixed at 500 W, for example, for a 150 kg satellite in VLEO or LEO. Consider a mission that requires a total impulse of 150 kNs, or a $\Delta V=1$ km/s. Several candidate metal propellants are considered: Mg, Cu, Zn, Mo, Ag, Cd, In, Sn, W, Pt and Bi. These metals span the mass range from 24.3 AMU (Mg) to 209 AMU (Bi). Their density spans the range from 1.74 g/cc (Mg) to 21.45 g/cc (Pt). To use the equation set 1 – 15 above, several physical parameters are required. These are listed in Table 3. The mean charge $\langle Z \rangle$, erosion rate ε_{mps} , arc burning voltage V_F , ion fraction f and ion speed U_{mps} are obtained from published literature on cathodic vacuum arcs [1, and references therein]. The atomic mass and density are physical parameters obtained from the web.

Propellant	$\langle Z \rangle$	M, AMU	erosion rate, kg/C	V _f , V	Ion fraction	U _{arc} , m/s	denisty, kg/m ³
Mg	1.54	24.3	3.3E-08	21.8	0.63	19836	1.74
Cu	2.06	63.6	3.34E-08	26.4	0.73	13229	8.94
Zn	1.2	65.4	5.52E-08	18.5	0.62	10364	7.14
Mo	2.91	95.9	3.40E-08	32.3	0.90	17408	10.22
Ag	2.14	107.9	7.41E-08	26	0.70	11172	10.5
Cd	1.32	112.4	9.46E-08	19	0.61	6846	8.64
In	1.34	114.8	8.05E-08	20.5	0.68	5875	7.31
Sn	1.53	118.7	8.31E-08	20.5	0.71	7022	7.3
W	3.21	183.84	2.71E-08	34.9	1.00	11144	19.3
Bi	1.2	209	1.72E-07	18.6	0.66	4734	9.81

Table 3: Physical parameters of the various MPIT candidate metal propellants

These fixed arc discharge parameters are used to derive thrust, ISP and other operational parameters for the different propellants using Eqs. 1 – 15. Table 4 lists the results for the case where the total input power P_{TOT} (see Eq. 13) is fixed at 500 W and the screen size is fixed at 100-mm. These values were chosen to enable a direct comparison with typical gridded ion engines or Hall thrusters operating at 500 W with $\approx$ 120-mm exit apertures.

The derivation begins by assigning a grid voltage V_b . Arc current, ion beam current, arc power, ion grid power, ISP and thrust are all derived using the equation set 1- 15. The input voltage is iterated to ensure that the total input power is 500 W. Eq. 1 gives the saturated Child-Langmuir output beam current I_{beam} . Eq. 3 gives the ion mass flow rate inside the grids (called m_{dot} grid ions in the table) and (by diving by 65% for the open area of the screen grid), the ion mass flow rate onto the screen grid, called m_{dot} screen ions in the table, is given by Eq.4 from the continuity requirement. The average mps current $\langle I_{mps} \rangle$ is given by Eq.5. But $\langle I_{mps} \rangle$ may also be derived from the output ion beam current as given by Eq. 6. Columns 6 and 7 of the table list these separately calculated arc currents and their equality provides a useful sanity check on the calculations.

SCREEN GRID DIAMETER =100mm; Total Power Fixed at 500W

Propellant	V _b , V specified	I _{beam} , A (from V _b)	m _{dot} grid ions kg/s	m _{dot} screen ions kg/s	<I _{mps} > A from m _{dot}	<I _{mps} > A from I _{beam}	P _{screen} TOT W from <I _{mps} >	T _{screen} deg. C from P _{screen}
Mg	834.7	0.397	6.5E-08	1.0E-07	5.06	5.06	29.5	556
Cu	877	0.306	9.8E-08	1.5E-07	6.50	6.50	19.8	477
Zn	983	0.273	1.5E-07	2.4E-07	7.30	7.30	19.1	471
Mo	908	0.311	1.1E-07	1.6E-07	5.63	5.63	37.2	606
Ag	1040	0.309	1.6E-07	2.5E-07	5.04	5.04	23.3	508
Cd	1112	0.262	2.3E-07	3.6E-07	6.51	6.51	12.5	397
In	1095	0.256	2.3E-07	3.5E-07	6.72	6.72	9.1	344
Sn	1107	0.273	2.2E-07	3.4E-07	6.03	6.04	12.5	396
W	864	0.219	1.3E-07	2.0E-07	7.78	7.78	18.7	467
Pt	1021	0.220	2.1E-07	3.3E-07	8.16	8.16	16.6	445
Bi	1309	0.235	4.2E-07	6.5E-07	6.06	6.07	11.0	375

Table 4: Operational parameters for MPIT at 500 W input power for fixed, 100-mm screen diameter

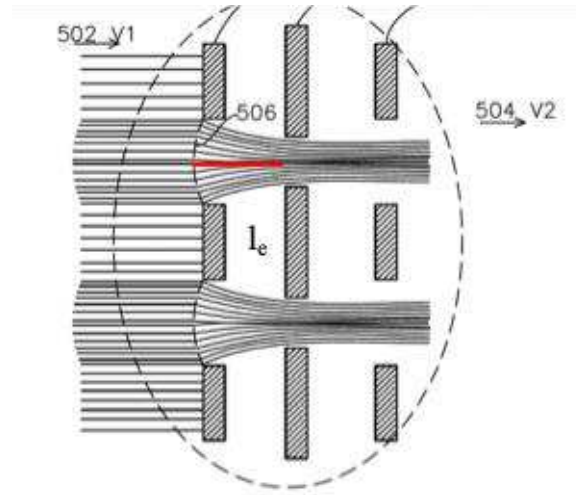


Figure 3: Ion rays inside the accel. - decel. grid structure. The red line shows the length l_e used in Eq. 9.

The last two columns show the total power into the screen (from radiation and ion heating) and consequently, the screen temperature when it is thermally isolated from the structure. It is useful to provide context for the parameter $(l_e)^2$ in Eq. 1. The incident plasma from the metal plasma source creates a concave meniscus at each of the screen grid holes, as shown in Figure 3. The red

line in the figure indicates the effective gap length l_e used in Eq. 9. Though the figure shows parallel ion rays to the left of the screen, the quasi-neutral plasma from the arc discharge has ions and co-moving electrons in a divergent conical pattern reminiscent of a supersonic (Mach-4 type) expansion. The plasma stops at the screen at the meniscus from which are drawn pure ions into the screen - accel. grid gap. This plasma meniscus should not penetrate the 2-mm hole and spill plasma into the accel. gap. To ensure this, the hole diameter should be no larger than about ~ 30 Debye lengths.

A handy formula for the Debye Length [10] is:

$$\lambda_D = \sqrt{\frac{kT}{4\pi n e^2}} = 743 * \sqrt{\frac{T}{n}} \quad (16)$$

Estimate of Debye Length at screen

mdot_arc	3.66E-07	kg/s
V_ions	10364	m/s
density	2.91E+10	/cc
Debye Length	7.54E-02	mm
hole dia/Debye length	27	#

Table 5: Estimation of Debye Length for Zn plasma near screen grid

The plasma electron density ($\#/cm^3$) at the screen is estimated from the mass flow, and mean ion charge ion speed (also the electron drift speed in the quasi-neutral plasma). The arc plasma mass flow rate and ion speed give the density at the screen of $\approx 3 \times 10^{10}$ /cc. Assuming a plasma temperature T of 3 eV, the Debye length is estimated to be $\approx 7.5 \times 10^{-2}$ mm as shown in **Table 5**. The ratio of the grid hole diameter to Debye length is ≈ 27 . A rule of thumb is that the hole should be $< 30 - 50$ times the Debye length, to ensure a concave meniscus at the hole that allows the electric field to draw ions into the grid gap. Our grid design meets this requirement. In practice, the grid parameters would be optimized for each propellant, as the arc discharge mass flow rate, temperature and ion speed are all different. But provided that the hole diameter/Debye length

criterion is met, one could adjust the hole diameter and inter grid gap to maximize the Child-Langmuir ion current drawn from the plasma.

The power on to the screen, P_{screen}^{mps} , and the temperature T_{screen} are calculated from Eqs. 8, 9 and 10.

Next, we calculate the ISP (Eq. 15), the thrust from the ion mass flow rate (Eq. 3) and ion speed (Eq. 14). Table 6 shows the calculated values.

Propellant	P_mps, W	P_b, W	ISP_mpi t s	T_mpit mN	T_HET @ same ISP mN	Imp./g Ns/g	DM_pro p for 150kNs kg	Prop.vol . L
Mg	169.0	331.0	10294	6.6	4.9	41	3.6	2.08
Cu	232.0	268.0	7547	7.2	6.6	35	4.3	0.48
Zn	231.8	268.2	6011	9.1	8.3	24	6.3	0.88
Mo	217.7	282.3	7426	7.8	6.7	43	3.5	0.34
Ag	178.9	321.1	6429	10.2	7.8	29	5.2	0.50
Cd	208.2	291.8	5114	11.6	9.8	20	7.5	0.87
In	220.2	279.8	5059	11.3	9.9	22	6.8	0.94
Sn	197.7	302.3	5346	11.5	9.4	24	6.2	0.85
W	310.8	189.2	5496	7.0	9.1	35	4.3	0.22
Pt	275.4	224.6	4669	9.8	10.7	25	6.0	0.28
Bi	192.9	307.1	3881	16.1	12.9	16	9.2	0.94

Table 6: Power into the MPS discharge, the ion optics grid, ISP and thrust of the MPIT: 500 W total power and 100-mm diameter grids

The first observation from the table is that the ISP values for the MPIT are much higher than typical values for Hall thrusters, but comparable to those for Xe Ion engines. Columns 2 and 3 of the table list the (separate) powers to the arc discharge of the mps and to the grids of the ion optics. These are constrained to sum to 500 W which is the assumed upper limit of available power in the 150 kg satellite of our example. To recapitulate, the voltage V_b was adjusted to make the total power 500 W.

The second observation is that the thrust of the MPIT is in the range of $\approx 7 \text{ mN} - 16 \text{ mN}$ for the different propellant choices. While these are lower than typical values for 500 W Hall thrusters, the ISP values are much higher. ***This is significant.*** The higher ISP implies lower propellant mass requirement for a given mission and lower storage volume. Couple this with the much higher density of most of the solid propellants (except for Mg) and the overall system volume is much lower by factors of many.

The last column of the table lists the thrust that would be delivered by a 500 W Hall thruster if it were to be operated at the same ISP values as the MPIT. Start with the benchmark thrust/power ratio of $\sim 29 \text{ mN/kW}$ at $\text{ISP} = 1500 \text{ s}$ for a Hall thruster, for example the published (<https://www.busek.com/bht600>) parameters for the Busek BHT-600 W thruster. Recall that this T/P ratio is not constant but a function of the ISP. For each MPIT propellant, the Busek Thrust is scaled from its nominal 1500s ISP to the higher ISP of the MPIT, to allow a more direct comparison. The values are very close to one another, which shows that the MPIT can match the thrust of HETs (and ion engines) for small satellite missions, but only at higher ISP. But this higher ISP is not a liability but an asset, as it drastically reduces the storage volume and mass of the thruster. Furthermore, the HETs cannot easily be operated at higher ISP because at higher anode voltages ($> 500 \text{ V}$) many Hall thrusters begin to lose efficiency [11] because wall losses increase, multiply charged ion fractions increase, electron temperature increases and there is greater plume divergence. To put it differently, HETs are well optimized for $< 2000 \text{ s}$ ISP and give higher T/P than the MPIT. But for higher ISP operation, the MPIT gives adequate thrust but with lower system volume and mass, due to the higher storage density.

Another interesting feature of the MPIT is that it is not limited by the usual tradeoff between higher ISP and lower thrust that is characteristic of HETs and all ion engines (including not only Xe ion

engines, but the Field Emission Electric Propulsion thrusters and the Iodine ion thrusters. This limitation is because the beam current scales as $(1/V_b)$. For higher ISP (higher V_b) the beam current is lower for a fixed power, and hence the thrust is also lower.

$$T = \dot{m} * u = \frac{I_{beam} M}{Ze} * \sqrt{\frac{2ZeV_b}{M}} \quad (16)$$

$$\frac{T}{P} = \frac{\eta * \frac{I_{beam} M}{Ze} * \sqrt{\frac{2ZeV_b}{M}}}{V_b * I_{beam}} = \eta * \sqrt{\frac{2M}{ZeV_b}} \quad (17)$$

The parameter η in Eq. 17 captures the thrust efficiency of the engine (itself a variable over the ISP range) and beam losses due to divergence or impartial ionization. If one plugs in 30% beam losses and a 40% thrust efficiency, Eq. 17 gives a T/P for a Hall thruster at 2000 s ISP, of 29 mN/kW, which is used in Table 6. Eqs. 16 and 17 show why the T/P ratio for diode driven ion engines that use a single power supply for the acceleration and ion generation decreases as the ISP (V_b) increases at a fixed power.

Hall thrusters do not have two metallic electrodes separated by vacuum as in ion engines or Iodine thrusters. Instead, there is a quasi-neutral plasma with an acceleration layer and an exit sheath only a few Debye lengths thick. Because ions are born inside the plasma, space charge is neutralized. The accelerating field is not a vacuum diode. Therefore, the classical Child-Langmuir current limits do not apply. Instead, the maximum current is determined by available ionization, a Bohm sheath criterion, electron cross-field mobility, the magnetic field topology, anomalous transport and channel losses.

Every electric thruster has some maximum deliverable ion current: in an ion engine: I_{max} is essentially the Child-Langmuir limit, scaling as $V^{1.5}$. In a Hall thruster: I_{max} is set by plasma generation and transport (empirically weaker than a $V^{1.5}$ roll-off). But in both types of ion thrusters there is the inverse roll-off of thrust with increasing ISP.

The MPIT does not suffer this tradeoff because the source of the beam current is the arc current which is independent of the beam power. This is illustrated by an example. The results are shown in Table 7. In this example, two parameters, the grid optics diameter and the accelerating voltage, were varied while keeping the total input power fixed at 500 W.

Propellant	D, mm	V _b , V input	P _{mps} , W	P _b , W	P _{TOT} , W	ISP _{mpit}	T _{mpit} , mN
Bi	172	771	258.1	241.9	500	2977	16.6
Bi	138	960	230.7	269.3	500	3323	16.5
Bi	118	1121	211.5	288.5	500	3591	16.4
Bi	104	1256	197.8	302.2	500	3801	16.2
Bi	98	1338	190.3	309.7	500	3922	16.1
Bi	91	1430	182.5	317.5	500	4056	16.0
Bi	83	1559	172.7	327.3	500	4234	15.8
Bi	79	1624	168.1	331.9	500	4322	15.7
Bi	75	1718	161.8	338.2	500	4445	15.5
Bi	70	1826	155.2	344.8	500	4583	15.3

Table 7: Variable accel. grid diameter and beam voltage: Bi MPIT at fixed 500 W power

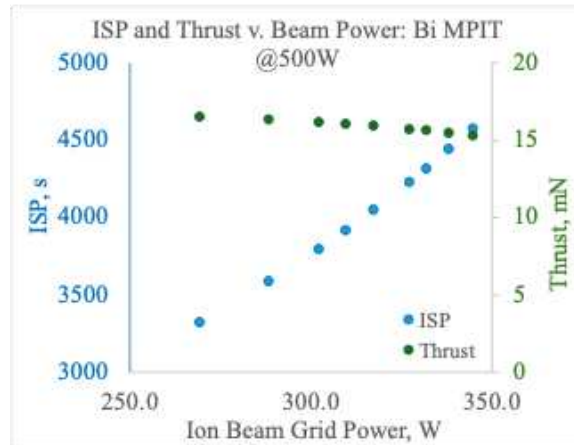


Figure 4: ISP (s) and thrust (mN) versus ion beam power (W): Bi MPIT at 500 W fixed total power

Figure 4 shows the ISP and thrust versus beam power (from the table) graphically. As the accel. voltage is increased from 771 V up to 1826 V, the ISP (blue dots) increases from ≈ 3000 s up to ≈ 4500 s. But the thrust (green dots 15 mN - 17 mN), is almost constant across the range. How is this possible?

The answer lies in the fact that the source of the beam current is a fixed fraction of the mps arc discharge current, see Eq. 6. For each voltage, the beam current required is supplied by a changing discharge power, for a fixed total power.

Figure 5 shows the thrust efficiency and propellant volume required to generate 150 kNs of total impulse, for a fixed total input power of 500 W. The thrust efficiency varies from 48% up to 66% as the ISP is increased. The propellant volume decreases from 1.29 L down to 0.84 L over the ISP range. For comparison, a Hall thruster operating at 2000 s ISP would require >10x this storage volume, both because its Xe density (1.6 kg/m^3) is 6x lower than the Bi density of 9.81 kg/m^3 and because of its lower ISP. The thrust values given in this paper are representative and will be different for fully optimized grids.

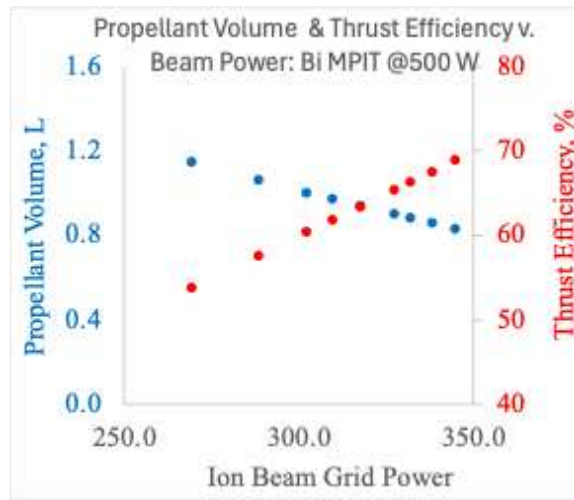


Figure 5: Thrust efficiency and propellant volume for 150 kNs total impulse at fixed 500 W power: Bi MPIT

The MPIT uses the mature MPT only as a source of ions, but significantly increases its thrust/power ratio and ISP, leading to candidate designs that come within a factor of two of Hall thruster outputs, while dramatically reducing the storage volume and thruster mass, as there are no magnets used.

For LEO and higher orbits, the MPIT could complement Hall thrusters. For example, a 250 kg satellite carrying a 1 kW HET along with two, 500 W MPITs would provide the mission planner

with the ability to use the HET for rapid maneuvers such as collision avoidance or rapid orbit insertion, while using the MPITs for slower maneuvers at much higher propellant utilization efficiency and with thrust only a factor of two lower. The combination would deliver 2x the total impulse of the HET alone, but with a lower than 2x total system volume and mass. The pulsed nature of the MPIT gives the mission planner an additional control parameter for precise attitude adjustment or docking maneuvers.

For VLEO, the MPIT offers another compelling advantage. The present preferred thrust option for VLEO missions is Air Breathing Electric Propulsion (ABEP). ABEP sucks in atmospheric molecules, ionizes them and ejects the ions from the rear of a satellite body that is aerodynamically designed to minimize frontal drag. Coatings are also used to minimize damage due to incident atomic oxygen impacting at ≈ 7.6 km/s. One problem with VLEO operation is the large variability of the ambient pressure. Solar activity changes the local density in unpredictable ways. The ABEP must be designed to accommodate these changes. If an MPIT engine is mounted on the rear of the spacecraft, it would provide a useful complement to ABEP. Firstly, the metal propellant is immune to atomic oxygen and furthermore, since it is housed in the rear, would be in the “wake” of the inrushing molecule flux, reducing the probability of damage to surfaces. Secondly, the high density of the metal propellants allows for useful total impulse in a compact volume.

Consider an MPIT operating with Zn propellant. Table 8 shows the main operating parameters. As for the Bi example, two parameters, the grid optics diameter and the accelerating voltage, were varied while keeping the total input power fixed at 1000 W.

Propellant	D, mm	V _b , V input	P _{mps} , W	P _b W	ISP _{mpit}	T _{mpit} mN	T (HET) mN @ same ISP
Zn	359	372	695.5	304	3698	16.8	26.3
Zn	284	481	638.4	362	4206	17.5	23.1
Zn	213	652	565.9	434	4894	18.1	19.9
Zn	179	778	522.2	478	5346	18.2	18.2
Zn	151	924	479.1	521	5827	18.2	16.7
Zn	129	1080	440.4	560	6299	18.1	15.4
Zn	113	1225	409.6	590	6710	17.9	14.5
Zn	99	1380	381.1	619	7122	17.7	13.6
Zn	89	1525	357.8	642	7486	17.5	13.0

Table 8: Variable accel. grid diameter and beam voltage: Zn MPIT at fixed 1000 W power

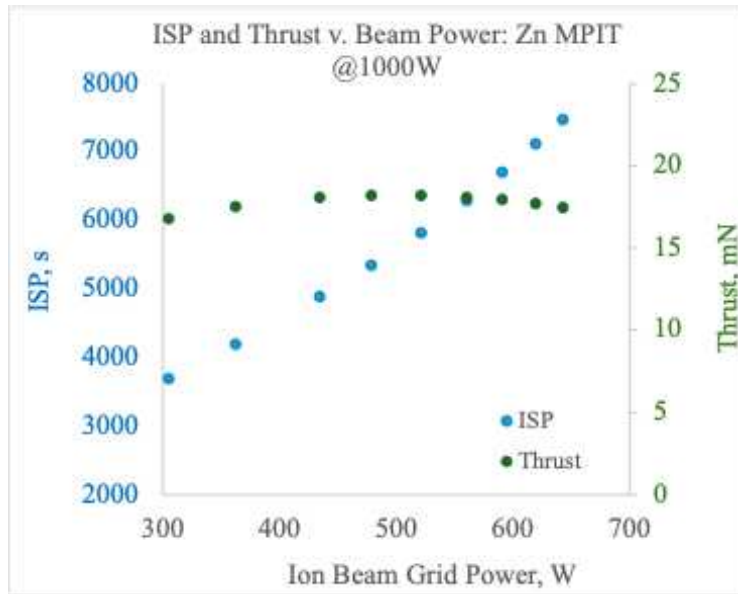


Figure 6: ISP (s) and thrust (mN) versus Ion beam power (W): Zn MPIT at 1000 W fixed total power

Figure 7 shows thrust efficiency and propellant volume for a 150 kNs total impulse, Zn MPIT at fixed 1000 W power. At an ISP of 5346 s, the thrust is 18.2 mN, the propellant mass required for 150 kNs is 7.1 kg, requiring a propellant volume of 0.99 L. Adding 1 L for the PPU makes this a ~2L thruster that complements the primary ABEP in a useful manner. The thrust efficiency is 48%, and comparable to the HET, but at much higher ISP.

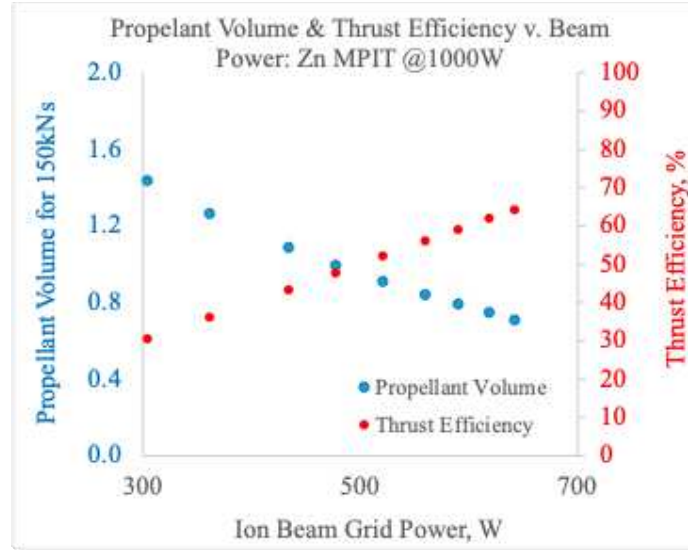


Figure 7: Thrust efficiency and propellant volume for 150 kNs total impulse at fixed 1000 W power: Zn MPIT

Consider VLEO operation at an altitude that requires say, 40 mN drag compensation for a 150-kg satellite. If solar activity forces an increase of thrust required to say, 60 mN, the MPIT is turned on and operated for the duration until the drag reverts to the nominal 40 mN condition. The total firing duration of the MPIT at 18 mN would be $(150 \text{ kNs}/18 \text{ mN}) \approx 96$ days. This interval is $\approx 10\%$ of a 3-year mission duration for the ABEP thruster. Two MPITs on the rear of a 150-kg satellite would provide up to 20% additional thrust capability to the mission, at a fraction of the volume occupied by ABEP.

The template outlined above may be used to evaluate any other conducting metal or alloy propellants for the MPIT. To provide background for the discussion on grid contamination in the next section, we first summarize the operating parameters for Cd and Sn propellants. The choice of Zn, Cd, Bi and Sn is motivated by binary and ternary eutectic or non-eutectic alloys whose primary aim is to provide a liquidus at low temperatures while showing a high volatility component at ≤ 500 deg. C. This would prevent metal mass pile up on the screen grid, blocking ion capture by the accel. grid.

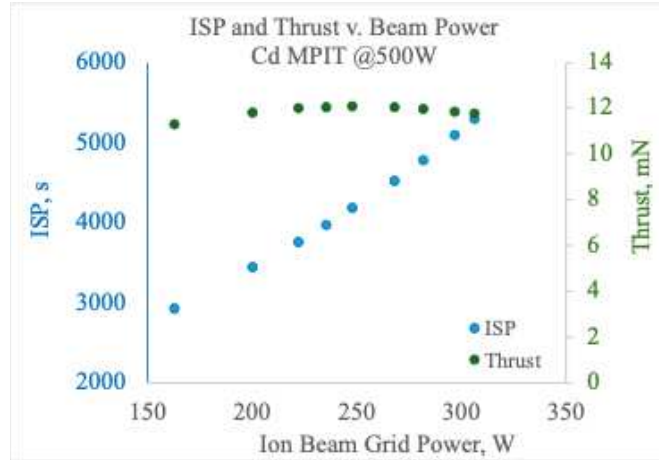


Figure 8: ISP (s) and thrust (mN) versus ion beam power (W): Cd MPIT at 500 W fixed total power

Figure 8 and Figure 9 show ISP (s), thrust (mN), thrust efficiency (%) and propellant volume (L) for a Cd MPIT at 500 W.

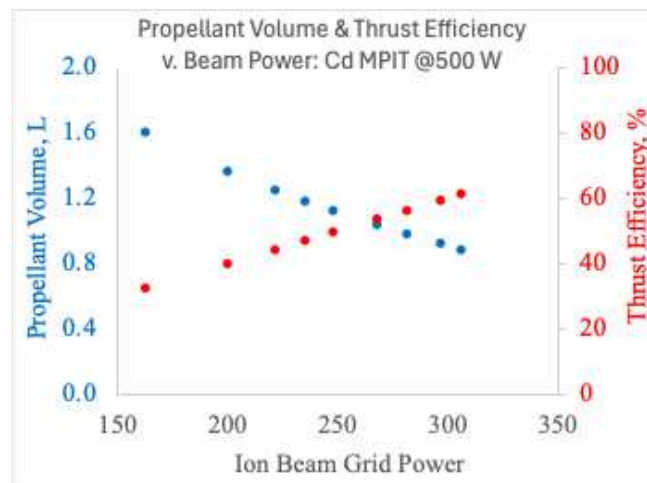


Figure 9: Thrust efficiency and propellant volume for 150 kNs total impulse at fixed 500 W power: Cd MPIT

Figure 10 and Figure 11 show ISP (s), thrust (mN), thrust efficiency (%) and propellant volume (L) for a Sn MPIT at 500 W.

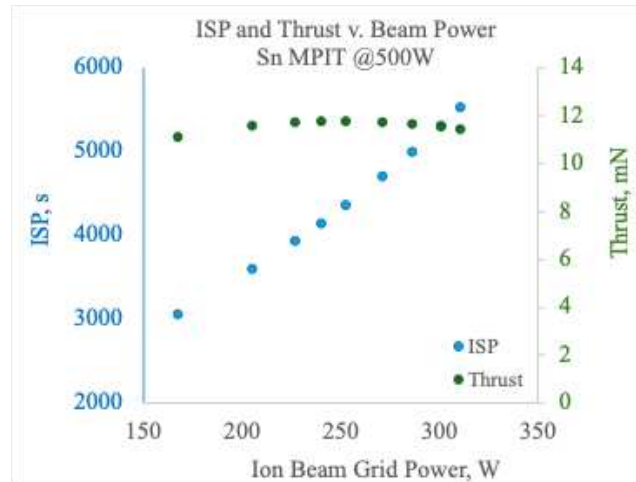


Figure 10: ISP (s) and thrust (mN) versus ion beam Power (W): Sn MPIT at 500 W fixed total power

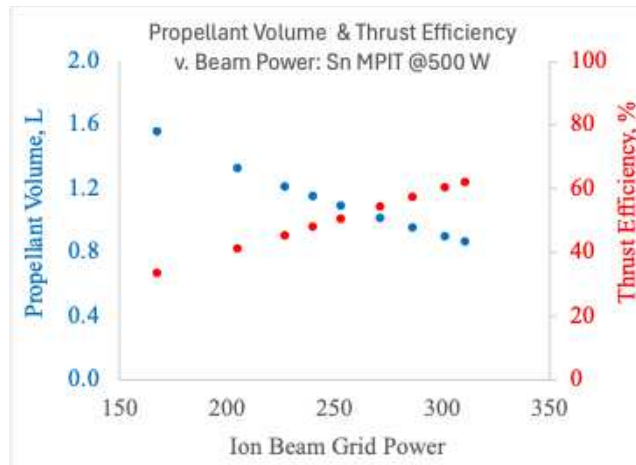


Figure 11: Thrust efficiency and propellant volume for 150 kNs total impulse at fixed 500 W power: Sn MPIT

This section has evaluated operating regimes for several candidate MPIT propellant from Mg to Bi. The tables and graphs reveal several features of the MPIT that set it apart from other gridded ion thrusters and Hall thrusters:

- The thrust remains roughly constant across a wide range of ISP
- The thrust/power ratio (T/P) is within a factor of two of that for Hall thrusters, but at much higher ISP. If Hall thrusters or gridded ion engines were to be operated at the same ISP, the T/P ratios would be very similar
- The thrust efficiency of the MPIT is $\approx 50\%$ and like that of the other thrusters

- Owing to use of solid propellants, the storage volume required for a given total impulse (or ΔV) is several times lower (by up to a factor 10) than for gas fed thrusters.
- The MPIT is designed from a plasma source (the MPT that has reached TRL-8 and of which nineteen versions are in orbit) and gridded ion optics that are a mature technology based on six decades of gridded ion engine development. Developing the MPIT to TRL-8 will not take long in the laboratory
- One possible limitation of the MPIT is that the metal atoms reaching the screen grid of the ion optics could pile up there and clog the pores

The next section considers the grid clogging question.

6 Grid contamination

This section considers grid contamination. In a Xe ion engine, the noble gas poses no contamination or accumulation problem to the grids. But the MPIT runs on metals. Up to 35% of the eroded cathode mass impinges upon the screen grid. Unless that mass fraction is ejected from the screen, it will build up a metal layer on the graphite or metal grid and eventually close the $\sim 2\text{mm}$ -dia. grid holes. For a well-designed accel.-decel. optic, a plasma meniscus would form at each of the ~ 1000 holes, from which ions would be extracted by the accel grid. The ions that do not pass through the holes would impact the screen surface between holes. The kinetic energy of the ions from the mps are [1]: Zn/36 eV, Cd/27 eV, Sn/30 eV and Bi/24 eV. Such ions are not energetic enough ($> 100\text{ eV}$ required) to burrow into the graphite surface and stick to it. But unless the grid is heated, some deposition is inevitable.

Table 9 and Table 10 summarize key parameters for the four propellants.

Propellant	D, mm	V _b , V input	T _{screen} , deg. C	T _{melt} , deg. C	T _{boil} , deg. C
Zn	126	779	409	419.5	907
Cd	102	1102	395	321.1	767
Sn	101	1094	393	231.9	2602
Bi	91	1430	396	271.4	1564

Table 9: Screen diameter, accel. voltage, screen temperature and ion beam ISP

The four propellant candidates for this discussion were chosen because of their low melting points and relative volatility, both useful attributes to avoid clogging the screen pores. Specific operating points were chosen for four candidates: Zn, Cd, Sn and Bi, selected to give screen temperatures close to 400 deg C, at which all the metals melt (see column 5 of Table 9). So, for the conditions chosen, all four metals will create molten pools on the screen surface. But this is only a necessary condition to avoid clogging of the pores. The sufficient condition is that the vapor pressure must be high enough to prevent atoms from landing on the molten pool and sticking to it. The design criterion for a suitable propellant is a low melting/liquid reservoir temperature along with substantial metal vapor pressure at ~400 °C. Zn is the best candidate from this standpoint.

But this is also where alloying could be a strategy. The alloy's main benefit is that it can create a low-temperature liquid reservoir, while retaining a volatile component. Zn alone can also do this as its vapor pressure is very high even near its melting temperature. But an alloy can reduce the melting point. For pure metals, the NIST reference table gives the following useful values: Cd reaches 10^{-1} Torr at 321 °C while Zn reaches 10^{-1} Torr at 405 °C.

Consider an alloy of Cd:Zn. The Cd–Zn eutectic melting temperature is around 265 °C, and the atmospheric-pressure eutectic composition is about 26.6 % (atomic of Zn). At 500 °C the simple ideal-mixture estimate gives roughly ~ 0.5 Torr, with most of the volatility from the Zn. The main

utility of the eutectic is to lower the melting temperature. The NIST database shows that the Cd–Bi eutectic is only 144 °C, while the Zn–Sn eutectic is ~199 °C.

In practice, some combination of these four metals might be used in alloy form to optimize the melting and volatility of the propellant as it accumulates on the screen. Table 9 shows that the mps radiation and its ion beam impingement on the screen would suffice to heat the screen to ~ 400 deg C. No auxiliary heater is required, but should one be required, the additional power required would be ~ 30 W. The screen diameter varies from 91 mm to 126 mm (column 2 of Table 9). If higher temperatures are required, the screen could be made smaller.

The last challenge is to ensure that the atoms that are reflected by the hot screen are captured in a “splashguard” that avoids build up on critical insulator surfaces that might eventually short out the arc plasma. This is a matter of proper geometric design with shielded features that allow metal build up without a deleterious ground path from the screen. With reference to Figure 1, the ions in the expanding plasma plume should reflect off the thin film of liquid metal on the screen and deposit onto the outer tube (shown in red in the figure). Only the ions near the axis would arrive normal to the screen and reflect to the cathode. But that would simply add mass back to the cathode to be eroded anew.

Propellant	ISP_mpit	T/P, mpit, mN/kW	Imp./g, Ns/g	DM_prop for 150kNs, kg	Prop.vol. L	Eff. %
Zn	5352	18.2	20.1	7.5	1.05	47.8
Cd	5092	23.7	18.8	8.0	1.12	59.3
Sn	5315	23.1	22.9	6.6	0.92	60.2
Bi	4056	31.9	16.2	9.2	0.94	63.5

Table 10: Thrust/Power ratio, Impulse/g, propellant mass for 150 kNs and thrust efficiency

Table 10 shows operating parameters of the four candidate thrusters. The T/P ratio varies from a low of 18 mN/kW for Zn up to 32 mN/kW for Bi. The impulse gram is calculated as the impulse

per gram eroded from the mps cathode, which is higher than the mass accelerated by the grids. For example, for Zn, only 65% of the eroded mass is transmitted through the screen grid. Only 95% passes through the anode and only 62% of the mass is ionized. The impulse/gram is calculated as that due to an effective mass of only $1/(0.95*0.65*0.62) = 38\%$ of the eroded mass. With this reduced mass, the impulse gram for the four propellants varies from ≈ 16 Ns/g for Bi up to ≈ 23 Ns/g for Sn. The propellant mass required to generate 150 kNs of impulse is 7.5 kg for Zn. Suppose that the screen is 150-mm in diameter and the mps cathode is ≈ 12 cm in diameter (to ensure full capture of the mps plasma by the screen grid when it is 1 cm from the cathode). If we assume that the erosion depth of the cathode is 10% of its diameter (1.2 cm in this case) then each cathode would erode ≈ 1 kg of metal. Eight such MPIT units would be required to give the 150 kNs required. Similar estimates for the other three candidates give a requirement of 7 units to generate the required total impulse.

The MPIT has an advantage that the PPU may be remote from the plasma generating head. The connection between PPU and head is by wires that carry the mps anode voltage (~ 45 V), the short pulsed optics voltages (~ 1 kV) and the return discharge ground path to the PPU, to isolate that from the spacecraft ground. Seven heads may be arrayed anywhere on the surface of the spacecraft, covering the required surface area of emission, but with the heads only ≈ 20 -mm deep, while the ≈ 1 L PPU units are housed elsewhere within the spacecraft volume. The control electronics would fire one head at a time until it is spent, then move to another head.

Smaller diameter versions of the MPIT may be arrayed along the 50-mm thickness of a DiskSat [12], driven by a common PPU deep inside the satellite, to provide impulse to the DiskSat with a low mass, low volume and efficient thruster.

Propellant	D, mm	V _b , V input	T _{screen} , deg. C	ISP _{mpit}	T _{mpit} , mN
Zn	45	1108	527	6381	2.80
Mo	45	1026	673	7895	2.37
Cu	45	987	533	8003	2.23
Cd	45	1245	445	5412	3.55
Bi	45	1463	421	4101	4.90

Table 11: Screen diameter, voltage, screen temperature ISP and thrust: DiskSat at 150 W power

Propellant	Imp./g, Ns/g	DM _{prop} for 20kNs, kg	Prop.vol. cc	Eff. %	# of MPITs
Zn	25.8	0.775	109	58%	3.4
Mo	46.4	0.431	60	61%	1.4
Cu	38.1	0.525	73	58%	1.8
Cd	21.5	0.929	130	63%	3.3
Bi	17.7	1.133	159	66%	3.6

Table 12: Impulse/g, Propellant mass and vol. (20 kNs impulse,) thrust efficiency and # of MPITs required

As an example, consider a total impulse requirement of 20 kNs for the DiskSat (10 kg mass given 2000 m/s ΔV). Table 11 and Table 12 show the calculations. For these simulations, the screen diameter was constrained to be 45-mm, to fit edge wise on the DiskSat, allowing for an outer tube that captures the reflected Zn vapor from the molten Zn pooled on the screen. The accel. voltage is higher for this case than for the larger (~100-mm) screens studied earlier for the 500 W thruster. We limit the total thruster power to 150 W, though the DiskSat can supply higher power. Column 4 of Table 11 shows that the screen is heated to a higher temperature in this case. This is desirable, as the higher temperature would create metal vapor at higher pressure for Zn and Cd. The ISP ranges from 4101 s to 8003 s and the thrust varies from 2.2 mN for Cu up to 4.9 mN for Bi. The T/P ratio for Cd is ≈ 24 mN/kW. This is a factor of two lower than for a Hall thruster, albeit at much lower ISP, but in any case, a Hall thruster is not practical for a DiskSat.

The ISP of the MPIT is much higher than that of a Hall Thruster which provides another advantage. Table 12 shows the impulse/g (of eroded mass from the mps cathode) the propellant mass and volume required for 20 kNs total impulse. The last column estimates the number of MPIT units required, if we assume that each cathode erodes to a depth of 8-mm, which has been observed in vacuum tests of the MPT. For Zn and Cd, 3 - 4 MPIT thrusters would suffice. The circumference of a 100-cm diameter DiskSat is ≈ 314 cm. The three MPITs would take up 15-cm along the circumference. Several more may be arrayed along the edge to boost the total impulse to higher values. Also, if a second PPU is accommodated in the DiskSat, units would be run in parallel at 300 W, to double the thrust to ≈ 6 mN. The three units at 150 W would sustain the ≈ 2 mN thrust for ≈ 120 days. For VLEO operation, multiple units could be placed all around the edge of the DiskSat to extend the lifetime to > 1 year. The MPIT propulsion architecture removes a major constraint of the DiskSat: the propulsion system does not have to be a monolithic box occupying the 50-mm thickness. The pulsed MPIT array effectively turns a set of discrete impulse generators into a quasi-continuous propulsion system by changing the spacecraft attitude as needed, to maintain a single thrust vector.

7 Summary

A new type of electric propulsion ion thruster is described. The Metal Plasma Ion Thruster (MPIT) draws ions from the plasma plume of the flight-qualified Metal Plasma Thruster (MPT) into a gridded acceleration region, to create a collimated metal ion beam whose thrust, ISP and total impulse are much higher than that of the native MPT plasma. The MPIT thrust is also higher than that of a comparable HET at the same ISP values. One possible limitation of the MPIT is metal buildup on the screen grid that closes the holes. Use of Zn could solve this problem as the power in the plasma hitting the screen is shown to be adequate to heat it to ≈ 400 °C. At this temperature,

the Zn will form a molten pool on the screen with a high vapor pressure that prevents significant buildup of a Zn film. Proper design of an outer tube to collect the reflected Zn atoms and to prevent this metallic film from shorting the arc and trigger electrodes will enable long duration operation of the MPIT with Zn propellant. By distributing the Zn over a larger surface area of the spacecraft and driving this distributed Zn mass with a common PPU, very large total impulse (>100 kNs) may be delivered from a thruster volume that is lower than that of comparable HETs or gridded ion engines. For missions requiring lower total impulse (smaller mass satellites) other propellants may be used but whose lifetimes may be limited by clogging of the screen pores.

8 Declarations

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Data availability: The datasets generated and analyzed during the current study are not publicly available because they contain proprietary information relating to the thruster design and its operation. Supporting experimental data are available from the corresponding author on reasonable request, subject to appropriate confidentiality restrictions

Code availability (not applicable)

Authors' contributions: M. Krishnan (MK) conceived the study and developed the analytical model. MK prepared the original manuscript.

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