Performance of a 100 Watt Radial Scaled Thruster with Anode Layer

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Abstract: It is presented the design of a 100 watt radial scaled Hall thruster (BUAA-TAL). The dimensions and parameters have been derived from the D-55 Thruster with Anode Layer. The magnetic field is produced by recently developed new SmCo 2:17 permanent magnets. A modular design has been selected to test several magnetic field configurations and several channel lengths. The magnetic field configurations were chosen to compare the influence in the thruster performance of the different magnetic field topographies and magnetic field gradients along the discharge channel. The thruster performance has been measured in the installations of the Joint Laboratory of Plasma & Propulsion (JLPP) using a torsional thrust stand. The best configuration provided thrusts between 2.6 and 7.8 mN with discharge powers ranging from 77 to 201 Watts. Anode efficiency and anode specific impulse varied between 17% to 34% and 1050 to 1600 s respectively.

Nomenclature

g	=	acceleration of gravity
I_{sp}	=	specific impulse
$\dot{m}_a$	=	anode mass flow rate
P_d	=	discharge power
T	=	thrust
η_a	=	anode thrust efficiency

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I. Introduction

IN recent years there has been an increased trend in the space industry for low powered missions[1-2]. Whereas Hall Thrusters have become the dominant technology of Electric Propulsion at medium and high power levels, there is still extensive effort to develop an efficient propulsion system that could work at low power levels[3-4]. Under this context, the Joint Laboratory of Plasma & Propulsion (JLPP) at Beihang University is developing its own series of thrusters with different technologies (PPT, Ion thruster, Magnetic-shielded thruster) for low discharge powers[5-6]. In this work it is presented the design of a 100 watt radial scaled conventional Hall thruster with anode layer. In section II the design of the thruster is explained, section III describes the different configurations, in section IV is introduced the experimental apparatus and finally in section V the results are commented.

II. BUAA-TAL design

A. Radial Scaling

Scaling theory is a common approach for designs of new thrusters[7-8]. It was decided to choose radial scaling because the driving scaling relations conduce to milder dimensional restrictions compared to other scaling methods where low power goals imply excessive miniaturization[9]. The -metallic walls- thruster with anode layer (TAL) was decided over the –ceramic walls- stationary plasma thruster (SPT) for manufacturability issues under a wider research project where it is intended to fully manufacture the thruster with 3D-printing methods. D-55 was selected as reference thruster due to the extensive available literature and its good performance[10-11]. The parameters of the reference thruster and the scaled thruster, together with the scaling relations are shown in Table 1. The channel length of the D-55 was not found in the literature but estimated to be 4mm. The width of the channel was obtained as sum of the distance between the anode tips that was found in ref.[12] and the distance between the anode tips and the guard rings published in ref.[11].

Table 1. Radial scaled parameters of the BUAA-TAL

	D-55 parameters	Radial scaling relations	BUAA-TAL
$\boldsymbol{P_d}$	$1230\,W$		$100\,W$
$\boldsymbol{U_d}$	$300\,V$	*constant*	$300\,V$
$\boldsymbol{L_c}$	$4mm$	*constant*	$4mm$
$\boldsymbol{h}$	$17mm$	$\propto P_d^{1/2}$	$4.9\,mm$
$\boldsymbol{r_c}$	$27.5\,mm$	$\propto P_d^{1/2}$	$7.8\,mm$
$\boldsymbol{\dot{m}_p}$	$4.52\,mg/s$	$\propto P_d$	$0.37\,mg/s$
$\boldsymbol{I_d}$	$4.1\,A$	$\propto P_d$	$0.33\,A$
$\boldsymbol{B}$	$223\,Gauss$	*constant*	$223\,Gauss$
$\boldsymbol{I_{sp}}$	$1786\,s$	*constant*	$1786\,s$
$\boldsymbol{T}$	$80\,mN$	$\propto P_d$	$6.4\,mN$

B. Permanent Magnets

For the source of the magnetic field it was decided to use permanent magnets over coils in order to reduce the amount of power required for the discharge and to prevent possible issues with and the thermal loads and the coils. It was used a recently developed high-temperature SmCo series 2:17 (Sm_2Co_{17}) permanent magnet[13] that simulations showed could prevent any saturation and demagnetization problems. Thermal simulations predicted maximum temperatures around 300ºC in the nominal operating point of 100 Watts, and maximum of 500ºC at 300 Watts.

C. Anode

Besides providing the potential difference with the cathode to create the electric field, the anode has the function of uniformly distributing the propellant around the channel for optimum plasma discharge. Because of the small dimensions of the thruster, it was only used one xenon injector into the thruster and the distribution around the azimuthal coordinate was achieved by use of a manifold with orifices which communicates the flow from the inlet of the anode to the discharge channel. A total of fifteen 0.5 mm diameter non-regularly spaced distributed holes were used. The anode was manufactured in three different components that were wielded together and a total of three fasteners. In Fig. 1 it is shown the cross-section of the different components of the anode. For operating conditions at powers larger than 220 Watts, the material required for the anode is molybdenum. However, for preliminary testing of the thruster it was decided to use 316 stainless steel and keep the operating range under 200 Watts.

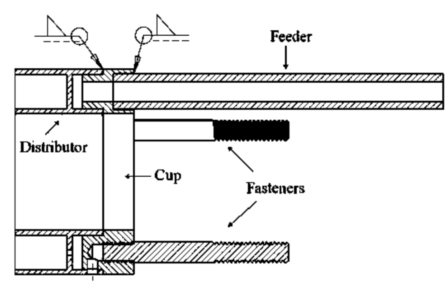

Figure 1. Anode cross section

III. Configurations

A. Channel Length

The actual channel length of the reference thruster was not found in the literature but estimated to be around 4 mm. To ensure certain flexibility in this dimension, the BUAA-TAL was designed to allocate the anode at different axial locations to allow for different channel lengths. For this purpose it was manufactured a set of three different ceramic insulators of 2, 2.5 and 3.5 mm thickness. These components not only accommodate the anode but ensure that electric insulation is achieved between the anode and the rest of the thruster, as required in TAL thrusters. A total of four different channel lengths were tested: 2 mm, 3 mm, 4 mm and 4.5 mm.

B. Magnetic Field

Regarding the magnetic field distribution, Hofer et al.[14] provide the basis that every magnetic field topography of a Hall Thruster should sustain for optimal performance. In particular, it is important to achieve symmetry of the magnetic field along the radial dimension with respect the centreline of the discharge channel, to attain a pronounced gradient of the magnetic field in the axial dimension between the anode and maximum magnetic field locations and to achieve a concave shape of the magnetic field lines at the exit of the discharge channel (known as plasma lens). Given the small dimensions and the compact design of the BUAA-TAL, it was difficult to accurately tailor that optimal magnetic field distribution and hence, different trade-off designs were proposed. The permanent magnets where combined with a set of stainless steel rings allowing to test different magnetic topographies and distributions. One configuration, considered as nominal, provides pronounced gradient from the anode to the location of the maximum magnetic field but with slightly degraded plasma lens shape. By reallocating the permanent magnets and the stainless steel rings, the plasma lens shape can be gradually improved at expense of decreasing the gradient of the magnetic field in the axial direction. This topography was used for the second configuration, called v2 configuration. The comparison of the two magnetic topographies and distributions, simulated with COMSOL®, can be seen in Fig. 2 and Fig. 3 respectively. In addition, two other configurations were designed using bigger permanent magnets to provide stronger magnetic fields, 415 G and 750 G respectively.

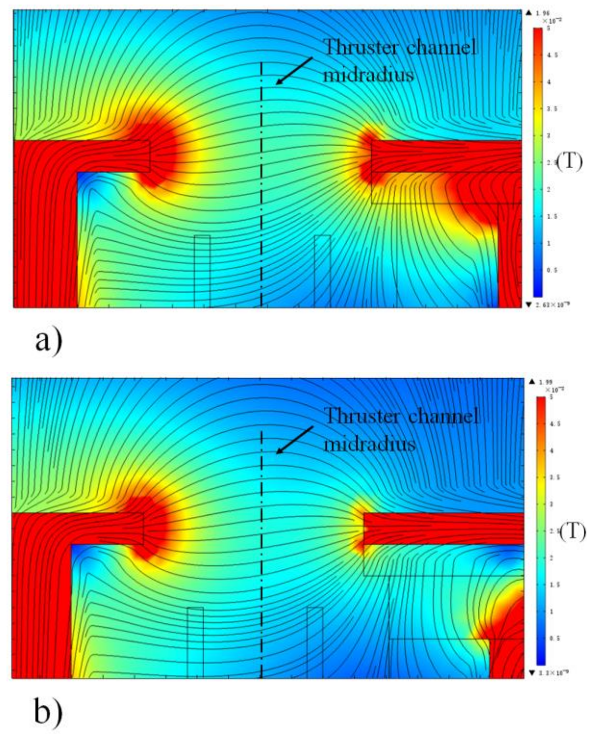

Figure 2. Magnetic field lines topography. a) nominal configuration b) v2 configuration

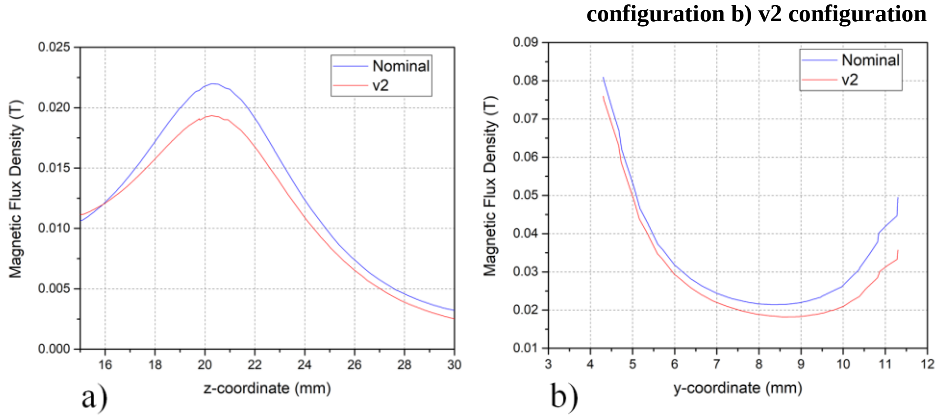

Figure 3. Magnetic field density distribution. a) axial coordinate b) radial coordinate

IV. Experimental Apparatus

A. Vacuum Chamber

BUAA-TAL was tested in a DMC-2500 vacuum chamber with a diameter of 2.5 m and a length of 5.5 m. It is equipped with four rotatory vane pumps, one roots vacuum pump and two high vacuum oil diffusion pumps. The minimum pressure attainable by the chamber pumping system is 10^{-4}Pa. The material of the chamber is stainless steel with low magnetic relative permeability.

B. Thrust Stand

To measure the thrust it was used a torsional-type thrust stand. The thrust stand is based on the linearity between the stress and strain of the pivot and it is equipped with a closed loop electromagnetic feedback. A capacitive sensor with a resolution of 0.2µm measures the displacement of the thrust stand and using a linear variable differential transformer (LVDT) produces an output voltage that is proportional to the thrust. The signal is recorded in a data recorder. Calibration of the thrust stand was performed before every test for all the configurations.

C. Cathode

For the experiments it was used a hollow cathode prototype developed by BVERI (Beijing Vacuum Electron Research Institue). The cathode was located at a distance of 8 mm from the exit plane of the thruster and 7 mm in the vertical direction from the thruster cover. A mass flow rate of 5 sccm had to be used as it was the recommended value of the manufacturer for safeguard of the cathode. The location and mass flow rate were the same for all the sessions.

V. Results and discussion

Experiments were carried out varying the discharge voltage from 150 V to 300 V in steps of 25 V and mass flow rates between 1.8 to 5 sccm in steps of 0.2 sccm for all different configurations. Anode specific impulse was calculated as:

$$I_{sp} = \frac{T}{g\dot{m}_a} \tag{1}$$

And the anode efficiency:

$$\eta_a = \frac{T^2}{2\dot{m}_a P_d} \tag{2}$$

Operating range was restricted to powers under 220 Watts in order to avoid overheating of the anode with thermal loads. Results showed the 4 mm channel length with nominal magnetic field to be the configuration with better performance, which is shown from Fig. 4 to Fig. 7.

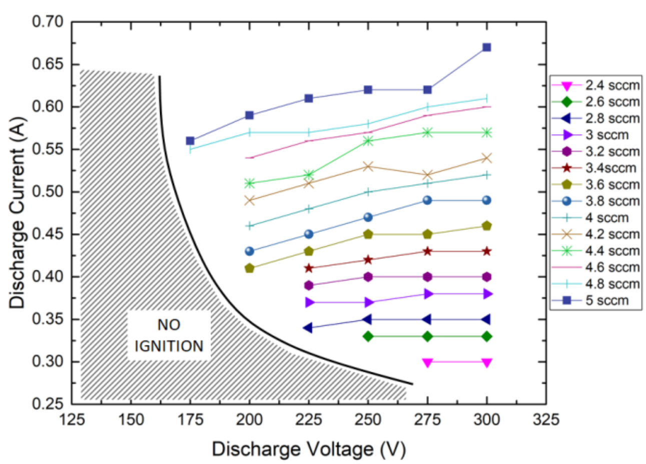

Figure 4. Discharge current vs. discharge voltage.

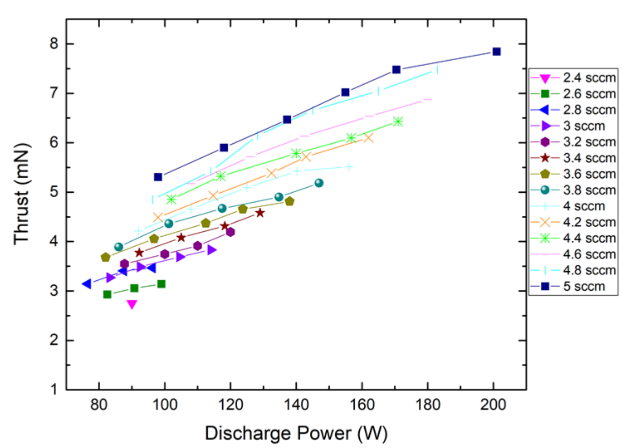

Figure 5. Thrust vs. discharge power.

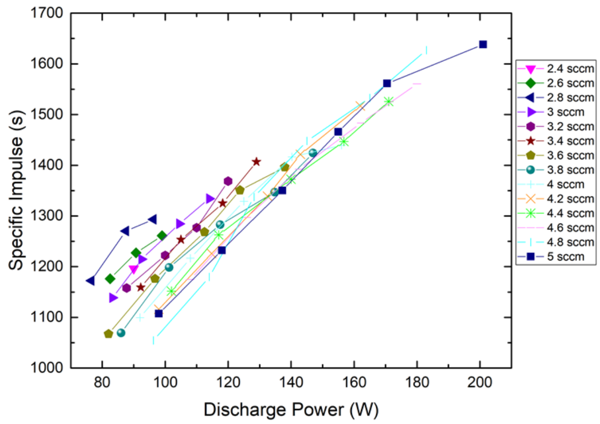

Figure 6. Anode specific impulse vs. discharge power.

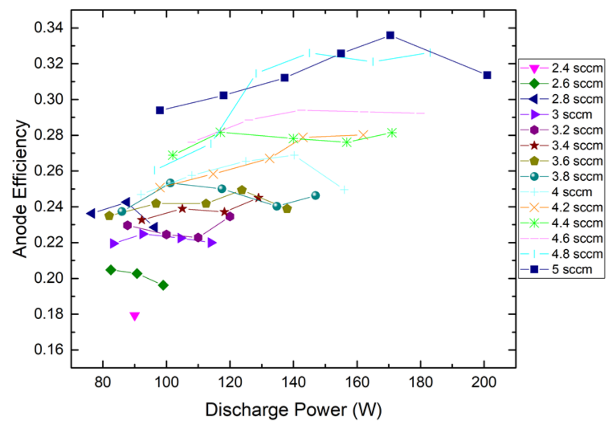

Figure 7. Anode efficiency vs. discharge power

In Fig. 4 is shown the volt-ampere characteristics of the BUAA-TAL. It can be seen that overall they follow the typical characteristics of a Hall thruster with stable operation and high propellant utilization[15]. There is a slight influence of the voltage in the discharge current but generally the increment in the discharge current is due to increments in the mass flow rate. Fig. 5 shows the thrust variation with discharge power. The thrust increases with both, the discharge voltage and the mass flow rate. The smallest thrust recorded for the 4 mm channel length configuration was 2.6 mN. The largest thrust of 7.8 mN was given at the operating point with the maximum discharge power recorded of 201 W (300 Volts, 5 sccm). The anode specific impulse vs. discharge power is shown in Fig. 6. Increments in specific impulse are mainly achieved by increments in the discharge voltage. The measured specific impulses ranged from 1050 to 1640 s. Fig. 7 shows the anode efficiency vs. discharge power. There is not a clear tendency in the behavior of the efficiency although it can be clearly seen that the efficiency is mainly affected by the mass flow rate rather than variations in the discharge voltage. The best efficiency achieved was 34% at 170 W (275 V, 5 sccm).

The 4.5 and 4 mm channel length configuration showed similar performance, presenting small variations. The 4.5 mm configuration generally provided slightly larger thrust and specific impulse whereas the 4 mm configuration always showed better efficiency. Overall the 4 mm channel length configuration was considered the best performance because the minor gains in thrust and specific impulse did not compensate the detriments in the efficiency. In contrast, the 3 and 2 mm configurations showed a notably decreased performance, especially the latter. Both performances could not provide thrusts greater than 5.5 mN and specific impulses over 1200s. However, the discharge current rose remarkably, given maximums between 0.8 – 0.9 A. This, together with the decrease in thrust and specific impulse, downed the anode efficiencies to values under 16% for the entire operating range. Probably the reason behind this detriment in performance comes in hand with the poor magnetic confinement of the anode. As the discharge channel is progressively reduced (the anode is taken downstream), the magnetic field topography is not effective anymore and poor electron confinement conduces to deficient ionization.

Regarding the different magnetic configurations, those that required greater magnetic field at the exit than the nominal design, i.e., the designs with 415 and 750 Gauss, could not be successfully ignited. It is suspected that it may be a problem of start-up process rather than operation, as it has been reported for other Hall thrusters using permanent magnets[5, 16]. It appears that using an electrode at intermediate potential between the anode and the cathode as precursor to initiate the plasma discharge can overcome the problem.

V2 configuration could be successfully ignited although its performance was notably below the performance of the nominal configuration. From Fig. 8 to Fig. 11 it is shown the comparison in performance between both configurations. The discharge could not be successfully maintained for voltages below 225 V and for mass flow rates under 3.2 sccm. In addition, discharge currents where higher than in the nominal configuration, leading to increased power discharges at the same operating points, shown in Fig. 8. In order to avoid overheating of the anode, those operating points with greater mass flow rate and discharge voltage were not tested. The joint contribution of these two phenomena provided a reduced operating range in comparison with the nominal configuration.

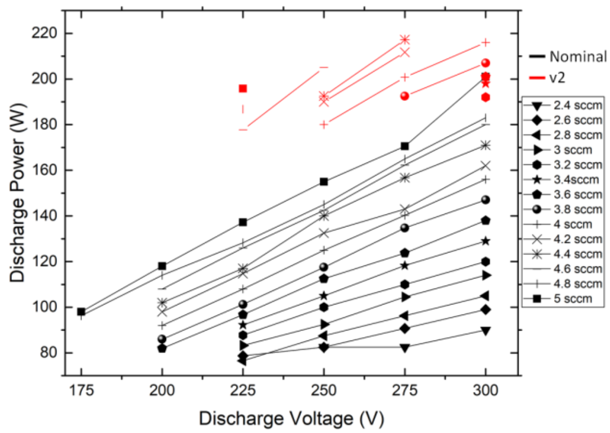

Figure 8. Discharge power vs. discharge voltage for the nominal and v2 configuration.

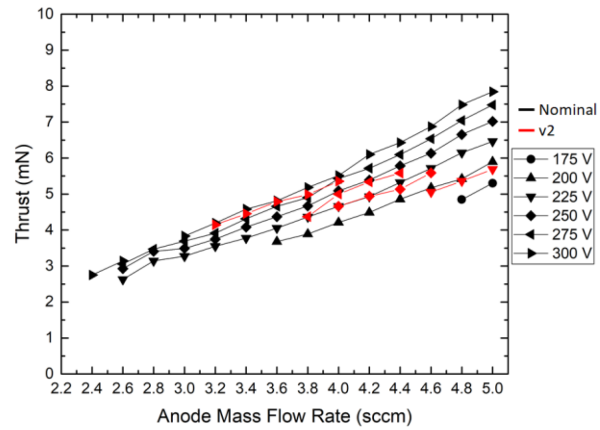

Figure 9. Thrust vs. anode mass flow rate for the nominal and v2 configuration.

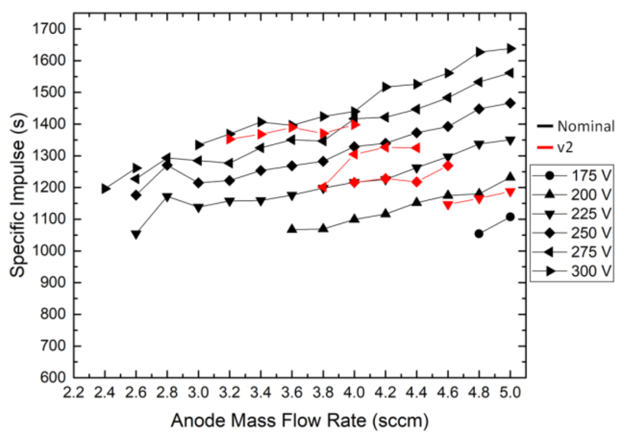

Figure 10. Anode specific impulse vs. anode mass flow rate for the nominal and v2 configuration.

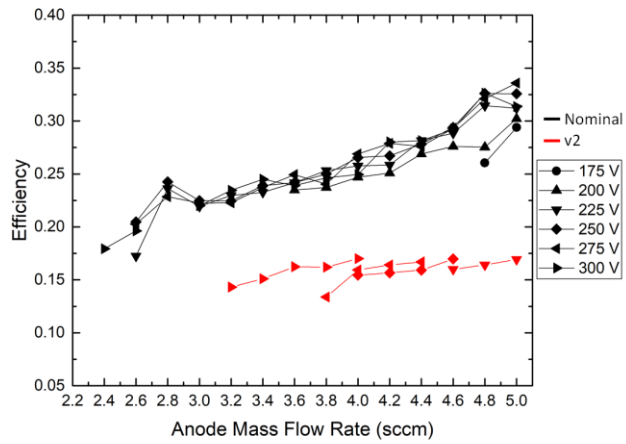

Figure 11. Anode efficiency vs. anode mass flow rate for the nominal and v2 configuration.

In Fig. 9 can be seen the comparison of thrust between both configurations. Whilst for 225 Volts the thrust was almost the same, from 250-300 V the thrust produced in the v2 configuration was about 0.5 mN lower than in the nominal configuration. A similar behavior is appreciated in Fig. 10. It can be seen that for 225 V the anode specific impulse is practically the same, whereas in the range from 250-300 V it decreases in values around 130 s. The anode efficiency can be clearly seen in Fig. 11 that was greatly reduced in the v2 configuration with a maximum of 17%. This abrupt variation in performance was achieved by altering the magnetic topography as illustrated in section III.B. It becomes patent the importance of optimizing the magnetic topography for desired performance as slight changes in the axial and radial distribution derive in drastic different performance of the thruster.

In Table 2 are shown the considered best operating points of the nominal configuration of thruster at 100 and 200 Watts power level. This preliminary performance of the BUAA-TAL thruster is in the range of actual state of the art low power Hall thrusters, as shown in Fig. 12 for 100 Watts power level and in Fig. 13 for 200 Watts power level.

Table 2. Performance of the BUAA-TAL thruster.

	Power (W)	Voltage (V)	Anode flow rate (mg/s)	Thrust (mN)	Isp (s)	Anode Efficiency
100W (High Isp)	96	275	0.27	3.5	1290	0.23
100W(High Thrust)	98	175	0.49	5.3	1110	0.29
200W	201	300	0.49	7.8	1640	0.31

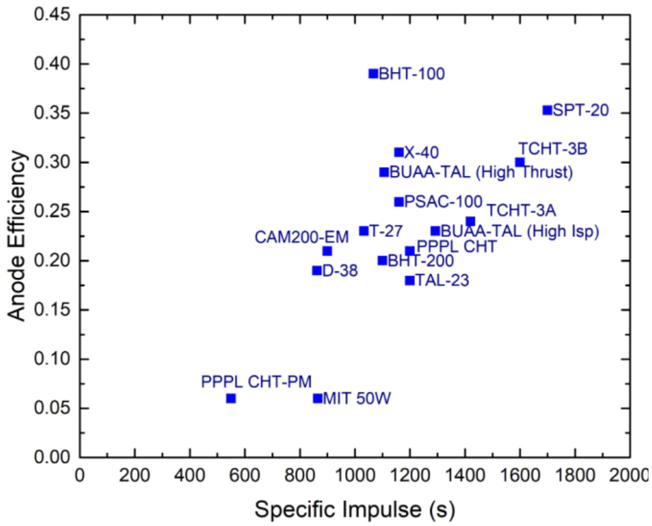

Figure 12. 100 W Hall thrusters comparison

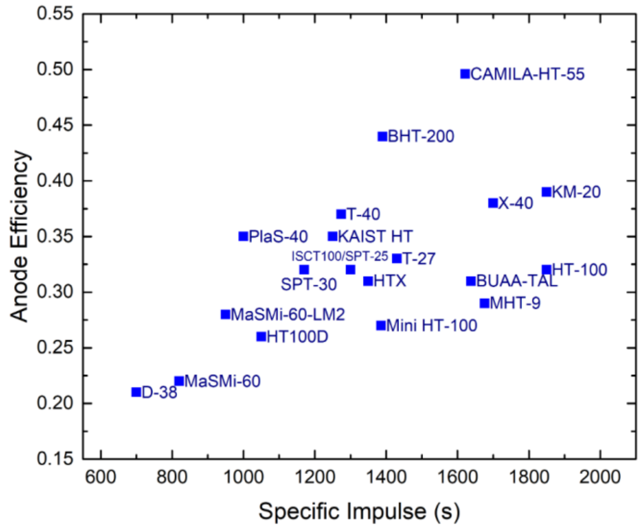

Figure 13. 200 W Hall thrusters comparison

Next efforts will be focused in studying the lifetime of the thruster and improving the performance. The experiments performed could not proportionate an estimate of the ratio of erosion of the thruster. Sputtering was observed but at the end of the sessions it could not be measured any observable difference in the geometry of the inner and outer guard ring. A molybdenum anode manufactured by 3D printing is intended to considerable improve the propellant distribution around the discharge channel, achieving a better uniformity of the plasma density in the azimuthal coordinate, enhancing the performance of the thruster. It will also allow to test the thruster are larger discharge powers. In addition, during the experiments it was observed how a metallic deposition was formed in the ceramic insulator where the anode was allocated. This deposition was observed to decrease the performance of the thruster with time and at the end of each session had to be manually removed. It is being studied the best ways to overcome this drawback.

VI. Conclusion

A TAL Hall thruster for low power levels has been designed. Different configurations related to the discharge channel length and the magnetic configurations were tested. The nominal configuration with a discharge channel length of 4 mm and a nominal magnetic field value near the channel exit of 223 Gauss probed to be the best configuration. Stable operation started at 175 V and 2.4 sccm, providing a minimum discharge power of 77 W. Operation was tested until an upper limit (for thermal reasons) of 201 Watts (300 V, 5 sccm), where the highest thrust of 7.8 mN and highest specific impulse of 1630 s where achieved. The best anode efficiency of 34% was obtained at 275 V and 5 sccm. For 100 Watts, the thruster provided a maximum thrust of 5.3 mN and a maximum Isp of 1290 s, with efficiencies ranging from 20% to 29 %.

Although the first experiments with the BUAA-TAL have been successful, there is still much room for improvement. Now that has been probed the most suitable configuration for the BUAA-TAL, attention will be focused in improving the design of the anode and avoiding the metallic deposition in the ceramic insulator.

Appendix

In Table 3 are the sources of the thruster data used in Fig. 12 and Fig. 13.

Table 3. Thrusters sources

Thruster	Source
X-40	O.Belikov *et al.*(1998)[17]
BHT-200	V. Hruby *et al.*(1999)[18]
MIT 50W	V. Khayms and M.Martinez-Sanchez (2000)[19]
T-27	L. Zakharenkov and G. Chislov (2001)[20]

D-38	
TCHT-3A TCHT-3B	A. Shirasaki *et al.* (2005)[21]
PPPL CHT	K. Polzin *et al.* (2005)[22]
SPT-20	D. Pagnon *et al.* (2007)[23]
PPPL CHT_PM	K. Polzin *et al.* (2009)[24]
TAL-23	M. titov *et al.* (2011)[25]
CAM200-EM	D. Katz *et al.* (2017)[26]
BHT-100	J. Szabo *et al.* (2017)[27]
PSAC-100	J. Lim *et al.* (2018)[28]
SPT-30	D. Jacobson and R. Jankovsky (1998)[29]
KM-20	A. Bugrova *et al.*(2001)[15]
HTX	A. Smirnov *et al.* (2002)[30]
SPT-25	V. Kim *et al.* (2003)[31]
HT-100	L. Biagioni *et al.* (2005)[32]
MHT-9	N. Warner and M. Martinez-Sanchez (2006)[33]
Mini HT-100	T. Misuri and M. Andrenucci (2008)[34]
CAMILA-HT-55	M. Kapulkin *et al.* (2011)[35]
HT100D	C. Ducci *et al.* (2013)[36]
PlaS-40	M. Potapenko *et al.* (2015)[37]
MaSMi-60	R. Conversano *et al.* (2015)[38]
T-40	J. Frieman *et al.* (2016)[39]
KAIST HT	C. Seunghun *et al.* (2016)[40]
MaSMi-60-LM2	R. Conversano *et al.* (2017)[41]
ISCT100	S. Mazouffre and L. Grimaud (2018)[42]

Acknowledgments

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