High Power Hall Thrusters Design Options

IEPC-2007-311

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Abstract

The development of an analytical scaling model coupled with a statistical database defines the opportunity of a wide and more flexible way of scaling Hall thruster in order to follow different design requirements. This paper is focused on the scaling methodology applied to a high power Hall thruster and it aims to provide different design options for this class of thrusters. In order to obtain a scaling model as effective and rational as possible, a vector of fundamental parameters, defining the thruster geometry and performances, has been created. Three geometric parameters has been chosen: the channel length, the channel width and the channel average diameter. The other two fundamental parameters are the gas number density in the injection plane and the applied discharge voltage. Given a set of basic physical relations which link these five parameters to all the other thruster performance, it is possible to build a scaling matrix. This matrix is a useful tool, which can then be used to obtain a new thruster on the basis of a chosen reference thruster. Here this methodology is used to obtain a preliminary configuration for a new 25 kW HET. Many possible options have been investigated during our analysis, carefully tailoring all the fundamental parameters in order to achieve specific performance goals. Two of the most interesting configurations are highlighted in this paper: a 25 kW HET working at high specific impulse, and a 25 kW HET able to provide a considerable thrust.

Nomenclature

b	channel width
B	magnetic field
d	channel mean diameter
e	electron charge
L	Channel length
I_{sp}	Specific Impulse
J	Current
$\dot{m}$	mass flow rate
n	Number density
P	Power
T	Temperature
t	Time
v	velocity
V	applied voltage
η	efficiency
ζ	scaling factor

I. Introduction

The present work describes an application of the HET scaling method developed at ALTA in the last few years[1,2,3]. This method has been refined several times and here the latest version[4] has been used to obtain a preliminary design of a 25 kW HET. Along the next section we will describe the chosen reference thruster, we will write down the fundamental physical equations for this kind of problem and we will briefly summarize how the method works. Then, we will provide a simple example of application just to give a taste of the wide range of possibilities offered by this method. Finally, we will attempt a preliminary sizing of a 25 kW thruster. Among all the possible configurations the most interesting ones will be analyzed in detail.

II. The Scaling Method

A. The Reference Thruster

Since we are dealing with a scaling method, the very first step is to chose a reference thruster. In ALTA we have a large database[5] covering many different HETs and among these we have chosen the SPT-100, which is the one that best suits our needs. Actually, there are three main reasons behind this choice:

1) there is a large amount of data available for SPT-100 (referring to many different operating points)
2) Russians SPTs had a significant flight experience, granting a certain reliability for the available data
3) SPT-100 works at an intermediate power level (~ 1 kW) and this makes it a good reference thruster both when scaling to high power levels and when trying to design a low-power HET

About the SPT-100 operating point, we have chosen the one corresponding to a power level of 1350 W. The table below contains parameters of interest at the desired operating point for our reference thruster. We will see next in this chapter that all the other relevant quantities can be obtained from this group of parameters by using appropriate physical relations.

PARAMETERS	Channel mean diameter	Unit of measure
d_{ref}	85	mm
b_{ref}	15	mm
L_{ref}	22	mm
V_{ref}	300	V

n_{ref}	1	n_{SPT100}
J_{D_ref}	4.50	A
P_{ref}	1350	W
$B_{\max\_ref}$	200	G
λ_{i_ref}	0.62	n.d.
λ_{diff_ref}	0.18	n.d.
ε_{w_ref}	0.25	n.d.
ε_{a_ref}	0.054	n.d.
ε_{i_ref}	0.136	n.d.

B. Fundamental Parameters

To build our scaling model we have to chose a group of fundamental parameters which can be independently tailored in the preliminary design phase. All the scaling relations that will be presented in the next paragraph will depend on these fundamental parameters. The chosen parameters are the following ones:

1) d channel mean diameter
2) b channel height
3) L channel length
4) V discharge voltage
5) n gas particle density in the injection plane

We have then a total of five parameters, the first three of them describing the geometry of the scaled thruster. Knowing their values, all the other data of interest can be derived by means of the physical equations governing the acceleration process inside a HET.

C. Fundamental Physical Relations for HET Scaling

Let us now introduce all the basic relations which allow us to obtain the thruster performance starting from the five fundamental parameters.

Writing the known data as ratios between the chosen value for a fundamental parameter and the corresponding reference value, we get:

$$\text{Known data: } \frac{d}{d_{ref}},\ \frac{b}{b_{ref}},\ \frac{L}{L_{ref}},\ \frac{V}{V_{ref}},\ \frac{n}{n_{ref}}$$

From the knowledge of these five ratios and of the reference thruster data, we can calculate all the other meaningful functioning parameters. As a first step, let us evaluate the total discharge current

$$J_D \propto \dot{m} \propto n \cdot M_{Xe} \cdot u_a \cdot d \cdot b \quad \Rightarrow \quad \frac{J_D}{J_{Dref}} = \frac{n}{n_{ref}} \frac{d}{d_{ref}} \frac{b}{b_{ref}} \qquad (2.1)$$

Since:

$$J_D \sim \frac{n \cdot V_D \cdot b}{B_{\max} \cdot L}$$

We have the following relation for the maximum magnetic field[6,7] intensity:

$$B_{\max} \propto \frac{n \cdot V_D \cdot b}{J_D \cdot L} \quad \Rightarrow \quad \frac{B_{\max}}{B_{\max\_ref}} = \frac{n}{n_{ref}} \frac{V}{V_{ref}} \frac{b}{b_{ref}} \left(\frac{L}{L_{ref}} \right)^{-1} \tag{2.2}$$

The HET's power is:

$$P = V_D J_D \quad \Rightarrow \quad \frac{P}{P_{ref}} = \frac{V}{V_{ref}} \frac{n}{n_{ref}} \frac{d}{d_{ref}} \frac{b}{b_{ref}} \tag{2.3}$$

The thruster global efficiency, η, can be written as:

$$\eta = \eta_{losses} \cdot \eta_J \cdot \eta_{vel} \cdot \eta_{\varphi} \cdot \eta_m \tag{2.4}$$

The loss factor η_{losses} takes into account the effect of the wall losses[8], the anode-sheath losses and of the energy lost for the ionization process. Its expression is the following one:

$$\eta_{losses} = \left(1 - \varepsilon_w - \varepsilon_a - \varepsilon_i\right) \tag{2.5}$$

Where $\varepsilon_w, \varepsilon_a, \varepsilon_i$ can be evaluated with our scaling model (since their value is known for the reference thruster):

$$\varepsilon_w \propto \frac{T_e^{3/2} \cdot n \cdot d \cdot L}{P} \quad \Rightarrow \quad \frac{\varepsilon_w}{\varepsilon_{w\_ref}} = \frac{L}{L_{ref}} \left(\frac{V}{V_{ref}} \frac{b}{b_{ref}} \right)^{-1} \tag{2.6}$$

$$\varepsilon_a \propto \frac{T_e^{3/2} \cdot n \cdot d \cdot b}{P} \quad \Rightarrow \quad \frac{\varepsilon_a}{\varepsilon_{a\_ref}} = \left(\frac{V}{V_{ref}} \right)^{-1} \tag{2.7}$$

$$\varepsilon_i \propto \frac{\dot{m}}{P} \quad \Rightarrow \quad \frac{\varepsilon_i}{\varepsilon_{i\_ref}} = \left(\frac{V}{V_{ref}} \right)^{-1} \tag{2.8}$$

The other four efficiency factors keep into account losses due to the electron current (η_J), the spread velocity loss (η_{vel}), the beam divergence loss (η_{φ}) and losses due to presence of neutral particles in the beam (η_m). They are usually considered constant and for them we have assumed the following values[9]:

$$\eta_J = 1 - \frac{J_e}{J_D} = 0.81 \qquad \eta_{vel} = 0.95 \qquad \eta_{\varphi} = 0.95 \qquad \eta_m = \frac{\dot{m}_i}{\dot{m}_i + \dot{m}_a} = 0.98$$

Our model allows us to evaluate the diffusion[10], ionization and acceleration fractions of the channel length, *L*. Indicating these fractions with the letter λ, we obtain:

$$\lambda_{diff} \propto \frac{\sqrt{T_e^{3/2} / n \cdot B_{\max}}}{L} \quad \Rightarrow \quad \frac{\lambda_{diff}}{\lambda_{diff\_ref}} = \left(\frac{n}{n_{ref}} \frac{L}{L_{ref}} \frac{V}{V_{ref}} \right)^{-1/2} \tag{2.9}$$

$$\lambda_i \propto \frac{u_{az}}{T_e^{3/2} \cdot n \cdot L} \qquad \Rightarrow \qquad \frac{\lambda_i}{\lambda_{i\_ref}} = \left(\frac{n}{n_{ref}} \frac{L}{L_{ref}} \right)^{-1} \tag{2.10}$$

$$\lambda_a = 1 - \lambda_{diff} - \lambda_i \tag{2.11}$$

Finally let us introduce the parameter α, which accounts for double ionized particles. A first guessing choice for α could be:

$$\alpha = \frac{\dot{m}_i^{++}}{\dot{m}_i} = 0.15 \quad \Rightarrow \quad \dot{m}_i^{++} = \alpha m_i \quad \text{and} \quad \dot{m}_i^{+} = (1-\alpha)\dot{m}_i \tag{2.12}$$

Where $\dot{m}_i$ is the total ion mass flow rate (comprising both, singly and double ionized particles)

It is now easy to calculate the scaled thruster performance:

Ion mass flow rate:
$$\dot{m}_i = \frac{(\eta_J J_D)}{e}(1+\alpha) M_{Xe} \tag{2.13}$$

Total mass flow rate:
$$\dot{m}_{tot} = \frac{\dot{m}}{\eta_m} \tag{2.14}$$

Ion exhaust velocity:
$$v_{ion} = (1-\alpha)\sqrt{\frac{2eV \cdot \eta_{losses} \cdot \eta_{vel} \cdot \eta_{\varphi}}{M_{Xe}}} + \alpha\sqrt{\frac{2 \cdot (2e) \cdot V \cdot \eta_{losses} \cdot \eta_{vel} \cdot \eta_{\varphi}}{M_{Xe}}} \tag{2.15}$$

Total thrust:
$$T = \dot{m}_i \cdot v_{ion} \tag{2.16}$$

Effective exhaust velocity and specific Impulse:
$$v_{eff} = \frac{\dot{m}_i \cdot v_{ion}}{\dot{m}_{tot}} = \eta_m v_{ion} \quad \Rightarrow \quad I_{sp} = \frac{v_{eff}}{g_0} \tag{2.17}$$

D. Building the Scaling Matrix

After having defined the five fundamentals parameters for our problem, let us change only one of them while maintaining all the others to their reference value. If we decide, for instance, to scale only the mean diameter *d*, we will come to the following conditions:

$$d = \zeta_d d_{ref} \quad \Rightarrow \quad \frac{d}{d_{ref}} = \zeta_d \quad (\zeta_d \text{ is the scaling factor for the HET mean diameter})$$

$$\frac{b}{b_{ref}} = \frac{L}{L_{ref}} = \frac{V}{V_{ref}} = \frac{n}{n_{ref}} = 1$$

By using equations (2.1)-(2.3) and (2.6)-(2.10) we can immediately build a scaling vector which relates the reference and the scaled quantities:

PARAMETERS	Channel mean diameter
d/d_{ref}	ζ_d
b/b_{ref}	1

L/L_{ref}	1
V/V_{ref}	1
n/n_{ref}	1
J_D/J_{D_ref}	ζ_d
P/P_{ref}	ζ_d
$B_{\max}/B_{\max\_ref}$	1
$\lambda_i/\lambda_{i\_ref}$	1
$\lambda_{diff}/\lambda_{diff\_ref}$	1
$\varepsilon_w/\varepsilon_{w\_ref}$	1
$\varepsilon_a/\varepsilon_{a\_ref}$	1
$\varepsilon_i/\varepsilon_{i\_ref}$	1

Repeating this procedure for each one of the other four fundamental parameters, we can define four new scaling vectors[3]. If we gather them all in a single matrix, we obtain the so called scaling matrix:

PARAMETERS	Channel mean diameter	Channel height	Channel length	Applied voltage	Gas inlet density
d/d_{ref}	ζ_d	1	1	1	1
b/b_{ref}	1	ζ_b	1	1	1
L/L_{ref}	1	1	ζ_L	1	1
V/V_{ref}	1	1	1	ζ_V	1
n/n_{ref}	1	1	1	1	ζ_n
J_D/J_{D_ref}	ζ_d	ζ_b	1	1	ζ_n
P/P_{ref}	ζ_d	ζ_b	1	ζ_V	ζ_n
$B_{\max}/B_{\max\_ref}$	1	1	$(\zeta_L)^{-1}$	ζ_V	1
$\lambda_i/\lambda_{i\_ref}$	1	1	$(\zeta_L)^{-1}$	1	$(\zeta_n)^{-1}$
$\lambda_{diff}/\lambda_{diff\_ref}$	1	1	$(\zeta_L)^{-1/2}$	$(\zeta_V)^{-1/2}$	$(\zeta_n)^{-1/2}$
$\varepsilon_w/\varepsilon_{w\_ref}$	1	$(\zeta_b)^{-1}$	ζ_L	$(\zeta_V)^{-1}$	1
$\varepsilon_a/\varepsilon_{a\_ref}$	1	1	1	$(\zeta_V)^{-1}$	1
$\varepsilon_i/\varepsilon_{i\_ref}$	1	1	1	$(\zeta_V)^{-1}$	1

III. Application of the Scaling Method: an Example

Given a certain reference thruster (SPT-100 in our analysis), the most straightforward procedure to scale a HET is as follows: first, choose the values for the five basic scaling factors, ζ; then, use the scaling matrix and equations (2.13)-(2.18) to obtain the performance of the new thruster.

Elsewhere it is possible to proceed in a more general way: this scaling method has 5 degrees of freedom (we can actually tailor the value of $\zeta_d, \zeta_b, \zeta_L, \zeta_V$ and ζ_n) so we can arbitrarily fix a desired value for 5 of the parameters contained in the scaling matrix, no matter if they belong to the group of the five fundamental ones. We can, for instance, set five conditions specifying the values of three fundamental parameters (say *d*, *b*, *n*) and two other ones (say *P* and $B_{\max}$). Then we will have to solve a system of 5 equations to find the ζ values that grant those conditions to be satisfied.

What is really interesting to show here is that, if all the scaling relations are in the form of power laws, then the system to be solved is always a linear one.

Let us explain this last assertion with a simple example, which provides also a comparison with real experimental data and so allow us to test the reliability of our method. Instead of directly choosing the values for $\zeta_d, \zeta_b, \zeta_L, \zeta_V$ and ζ_n, we decide to fix the desired values for *d*, *b*, *L*, *V* and *P*. We choose these five values which are relative to the 50 kW NASA M-457 HET:

$d = 329$ mm
$b = 128$ mm
$l = 83$ mm
$P = 50000$ kW
$V = 500$ V

According to the scaling matrix, we can write the following five equations in the unknowns $\zeta_d, \zeta_b, \zeta_L, \zeta_V$ and ζ_n:

$$\begin{cases} \dfrac{d}{d_{ref}} = \zeta_d \\ \dfrac{b}{b_{ref}} = \zeta_b \\ \dfrac{L}{L_{ref}} = \zeta_L \\ \dfrac{P}{P_{ref}} = \zeta_d \cdot \zeta_b \cdot \zeta_V \cdot \zeta_n \\ \dfrac{V}{V_{ref}} = \zeta_V \end{cases} \quad \text{taking the logarithm} \Rightarrow \quad \begin{cases} \ln\left(\dfrac{d}{d_{ref}}\right) = \ln \zeta_d \\ \ln\left(\dfrac{b}{b_{ref}}\right) = \ln \zeta_b \\ \ln\left(\dfrac{L}{L_{ref}}\right) = \ln \zeta_L \\ \ln\left(\dfrac{P}{P_{ref}}\right) = \ln \zeta_d + \ln \zeta_b + \ln \zeta_V + \ln \zeta_n \\ \ln\left(\dfrac{V}{V_{ref}}\right) = \ln \zeta_V \end{cases}$$

Passing to the logarithms we get a linear system of equations, whose solution is easy to find. If we write the system in the standard form $\vec{B} = Q\vec{X}$, indicating with Q the matrix of coefficients, we have:

$$\underbrace{\begin{bmatrix} \ln\left(d/d_{ref}\right) \\ \ln\left(b/b_{ref}\right) \\ \ln\left(L/L_{ref}\right) \\ \ln\left(P/P_{ref}\right) \\ \ln\left(V/V_{ref}\right) \end{bmatrix}}_{\vec{B}} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}}_{Q} \cdot \underbrace{\begin{bmatrix} \ln \zeta_d \\ \ln \zeta_b \\ \ln \zeta_L \\ \ln \zeta_V \\ \ln \zeta_n \end{bmatrix}}_{\vec{X}} \quad \Rightarrow \quad \vec{X} = Q^{-1}\vec{B}$$

Knowing the vector $\vec{X}$ we can immediately evaluate the five scaling factors. Substituting the values in our example, we get the following scaling factors:

$$\zeta_d = 3.773, \quad \zeta_b = 9.834, \quad \zeta_L = 3.870, \quad \zeta_V = 1.667, \quad \zeta_n = 0.612$$

The thruster performances will then be:

Parameter / Thruster	**NASA-457 HET**	**50 kW HET obtained with the scaling method**
d [mm]	329	329
b [mm]	128	128
L [mm]	83	83
V [V]	500	500
P [W]	50000	50000
mass flow rate [mg/s]	**93.9**	**98.2**
I_{sp} [s]	**2512**	**2478**
Thrust [N]	**2.33**	**2.39**
Overall efficiency	**0.58**	**0.59**

The results are in excellent agreement with the experimental data.

IV. Comparison with real Data

This paragraph shows the validity of the new scaling model. This model has been used to scale HETs both at high and low powers. The results so obtained are compared with the data from the database realized at ALTA-Centrospazio (a database containing geometric dimensions and performance parameters for several existing HETs built in Europe, United States, and in the ex Soviet Union).

The following figures compare the experimental data with the results coming from the scaling model.

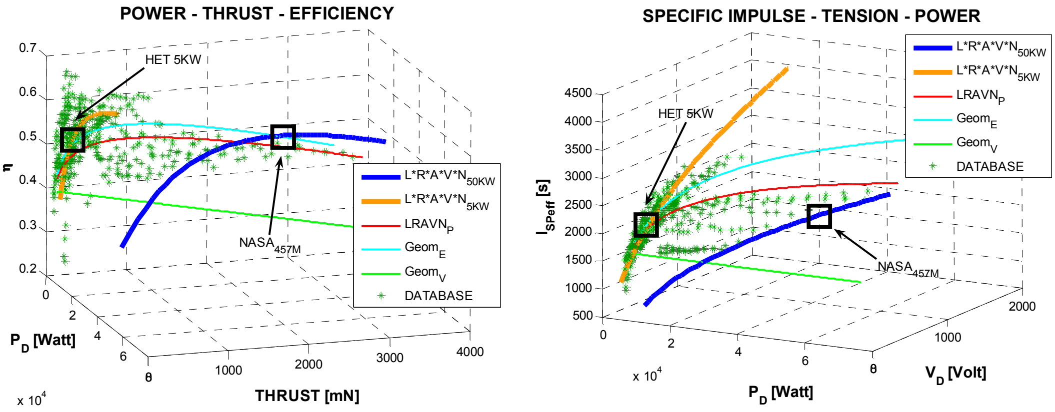

Fig. 1: High Power HETs: comparison of the scaling model results with experimental data

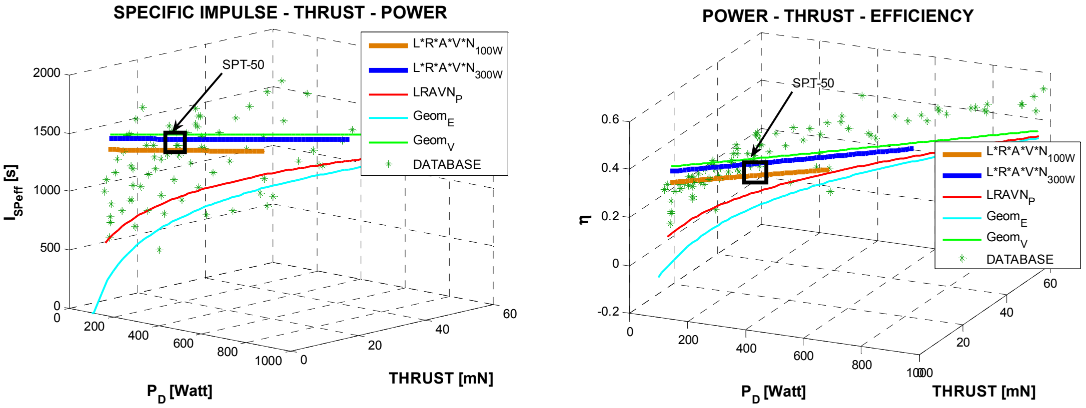

Fig. 2: Low Power HETs: comparison of the scaling model results with experimental data

The diagrams also show the results of the previous scaling model (Battista-Piliero) and the results of the new model with power as the only constraint (orange curve).
As we can see from the figures above, the new models provide results that are closer to the real data.
In addition the scaling model has been here applied to four HET devices, two working at high power (5 KW and 50 KW) and two working at low power (100 Watt and 300 Watt), chosing suitable geometrical and performance constraints. We can see that the model faithfully reproduce the data of the 5KW HET by ALTA-Centrospazio and the thrust by NASA M-457 (see previous chapter). Also the 100 Watt and the 300 Watt scaled thrusters are very similar to the XHT-100 and SPT-50.

V. Preliminary Design of a 25 kW HET

Let us now adopt our scaling method to obtain a preliminary design for a 25 kW thruster. Since the application of this method is quite straightforward we have investigated a large number of possible configuration with this power level. Our analysis has led to point out two most interesting configurations, the first for a high specific impulse thruster, the other one for a “high” thrust device (maybe the word “high” is not appropriate, since we are still dealing with low thrust devices).

A. 25 kW HET with High Specific Impulse

To obtain a high specific impulse we need a strong field to accelerate the particles. As a consequence the applied voltage assumes high values. The mean diameter has been kept rather low, in order to limit the total size of the thruster. The channel has a *L/b* ratio of 1.29, which is comparable to the SPT-100 *L/b* ratio (=1.6). The gas density in the injection plane is unchanged with respect to SPT-100. As a whole, we have the following configuration:

	High Specific Impulse HET
d [mm]	200
b [mm]	35
L [mm]	45
V [V]	920
n [n_{SPT100}]	1
P [W]	25000
B_{max} [G]	**300**
mass flow rate [mg/s]	**26.7**
I_{sp} [s]	**3446**
Thrust [N]	**0.902**
Overall efficiency	**0.63**

E_{eff} [V/m]	26867 (for SPT-100 it is 45000)

Analysing the overall performances, we can see that a good efficiency has been achieved together with a remarkable specific impulse (and this was our primary goal). The thrust is instead quite low and if a higher value of it is needed we have to switch to a different HET configuration, as shown in the next paragraph.

B. 25 kW HET with High Thrust

To obtain a high thrust we need to process a higher mass flow rate. So, in order to keep the initial gas density to an acceptable value, we have chosen a larger diameter and a larger channel height. Here the channel has a different shape, with a lower L/b ratio (=0.48) and the applied voltage is far lower than in the previous case. The high thrust HET configuration has the following parameters and performances:

	High Thrust HET
d [mm]	250
b [mm]	62
L [mm]	30
V [V]	275
n [n_{SPT100}]	1.5
P [W]	25000
B_{max} [G]	**135**
mass flow rate [mg/s]	**88.7**
I_{sp} [s]	**1713**
Thrust [N]	**1.491**
Overall efficiency	**0.51**
E_{eff} [V/m]	14286 (for SPT-100 it is 45000)

The efficiency is not as high as before, because in this configuration the loss factor, η_{losses} , has a relevant impact on the overall performance. This is mainly due to the reduction of the applied voltage (according to the scaling matrix, it is apparent that a lower voltage means a higher value for $\varepsilon_w, \varepsilon_a, \varepsilon_i$). However, the total thrust is around 1.5 N, which is indeed remarkable for this kind of devices. A concern for the high thrust HET configuration could be the low value of the effective electric field, which is less than one third of the SPT-100 E_{eff}.

Here follows a sketch of both configurations:

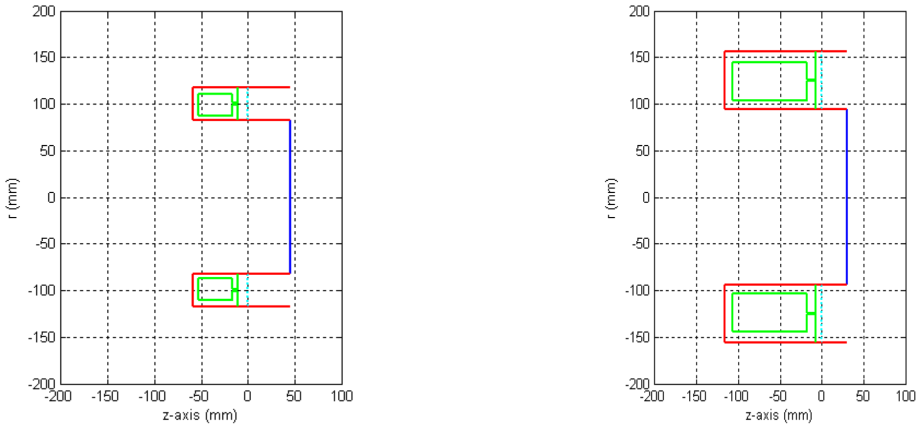

Fig. 3: sketch of the two chosen configurations for a 25 kW HET. A high specific impulse configuration (on the left), and a configuration providing a higher thrust (on the right)

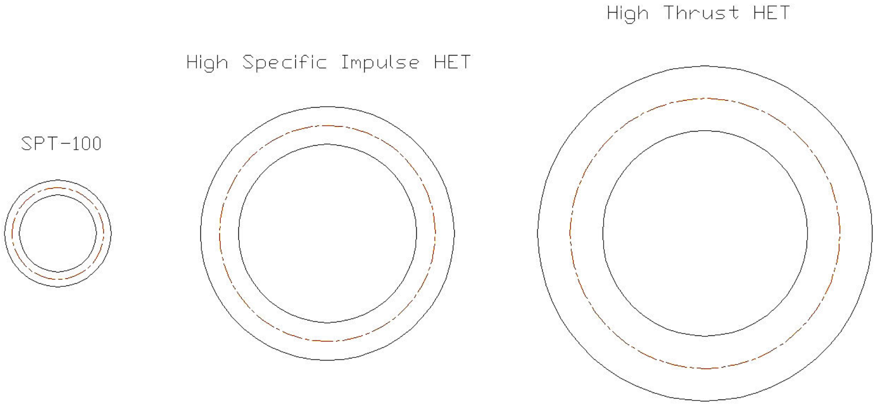

Fig. 4: SPT-100 cross section compared with the cross sections of the 25 kW HET (both configurations)

VI. Conclusion

In the present work we have applied the HET scaling method developed in ALTA to define two possible configurations for a 25 kW HET thruster. The first one is a high specific impulse configuration, while the other one is designed in order to provide a higher thrust.

The high specific impulse configuration has a channel shape which resembles the one of SPT-100 and the expected efficiency is over 60%.

The second configuration obtained is able to provide twice the thrust, but it suffers an increase of wall losses and ionization losses which directly affect the overall efficiency. The channel, in this second configuration, has a *L/b* ratio considerably lower than in the previous case. Besides, this thruster is larger than the high specific impulse HET, because it has been necessary to increase the diameter, *d*, to avoid an excessive value for the initial gas density (notice that here the mass flow rate is larger, in order to increase the thrust).

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