Spectroscopic Temperature Measurement in a Applied Field MPD

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In this paper the temperature of the plasma inside an MPD thruster has been measured with and without applied magnetic field using spectroscopic measurement. The obtained spectra show the presence of C++, C+ and F atoms while the lines relative to C, F+ and F++ are out of scope. Using the measured line intensities, formulating three different sets of hypotheses and assuming that the corona equilibrium is valid for this plasma the temperature values have been calculated. The temperatures found are around 3 eV and show small variations with the application of magnetic field confirming.

Nomenclature

A	=	area
B	=	applied magnetic field
b	=	coefficient
C	=	carbon
$C^{+}_{1,2,3}$	=	emission line of single ionized carbon λ_1= 514.65 nm, λ_2= 569.6 nm, λ_3= 697.3 nm
D	=	spectrometer – cathode distance
E	=	shot energy
F	=	thrust, fluorine
$F_{1,2,3}$	=	emission line of single ionized carbon λ_1= 623.96 nm, λ_2= 685.6 nm, λ_3= 723.8 nm
I	=	current

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In	=	emission line intensity
k_b	=	Boltzman constant
L	=	collimator length
Lu	=	luminance
$\dot{m}$	=	mass flow rate
m_i	=	ion mass
n	=	electron particle density
p	=	pressure
R	=	radius of the area seen by the spectrometer
r	=	collimator radius
T_e	=	electronic temperature
v	=	velocity
x	=	abscissa
μ	=	vacuum magnetic permeability

Subscript

anode	=	relative to the anode
exp	=	experimental
max	=	maximum
min	=	minimum
spectro	=	relative to the spectrometer
th	=	theoretical

Superscript

+	=	single ionize
++	=	double ionized

I. Introduction

THIS paper deals with the spectrometric analysis of the jet of a solid propellant (Teflon), quasi-steady, MPD thruster. The thruster is powered by a capacitive PFN with a total capacitance of about 60 mF, a maximum voltage of 450 V and an instantaneous power of few Megawatts during shots of about one millisecond

The MPD is operated both in self magnetic field and applied magnetic field mode.

The objective of this research is the measurement of the electronic temperature inside the thruster, of the influence that the applied magnetic field has on it, and the observation of the species (atoms and ions) that are present inside the plasma jet with consequent calculation of the ionization level.

II. Experimental Apparatus

To analyze the plasma jet a spectrometer with a detecting range between 500 nm and 800 nm has been used. The spectrometer properties are shown in Table 1.

Table 1 Spectrometer specifications	
Dimension	89.1 x 63.3 x 34.4 mm
Weight	190 grams
Detector	Toshiba TCD1304AP Linear CCD Array
Detector range	495 – 795 nm
Signal-to noise ratio	300:1 (at full signal)
Sensitivity	130 photons/count at 400 nm 60 photons/count at 600 nm
Optical resolution	~ 1.5 nm
Integration time	10 µs at 65 seconds
Stray light	< 0.05% at 600 nm; 0.1% at 435 nm

A collimator has been used to focus the spectrometer view on the core of the thruster. The collimator length and radius have been chosen such in a way that the light collected by the spectrometer comes from a circular area of radius 0.5 cm centred on the thruster axis.

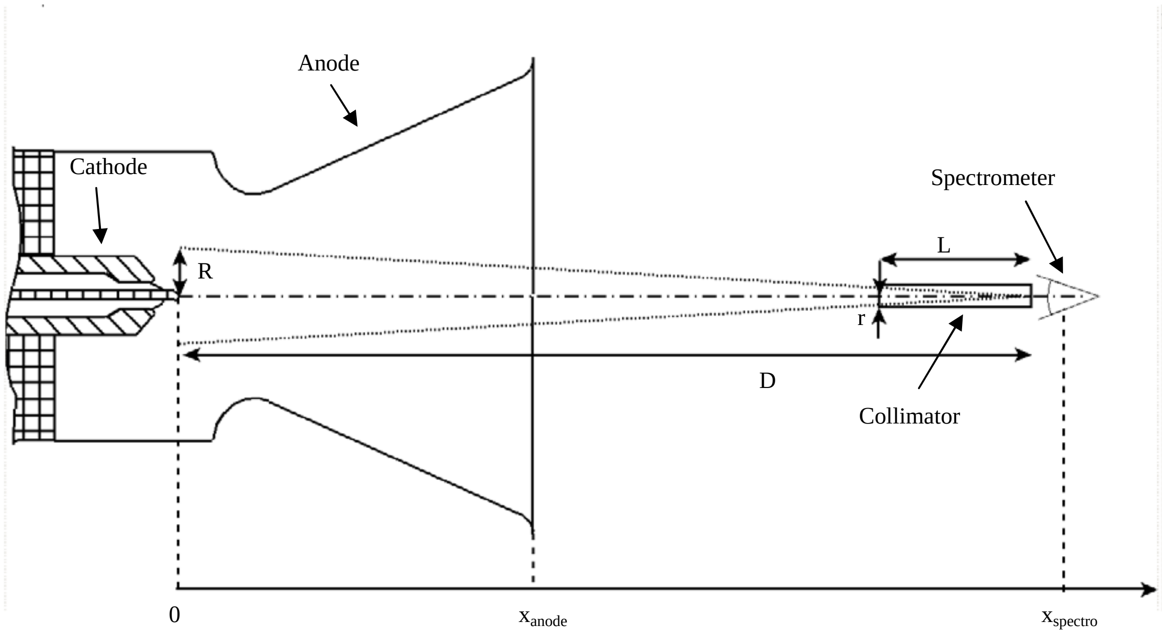

Figure 1. Experimental setup (figure not in scale).

Being the spectrometer-thruster distance D = 1 m the collimator dimensions have been chosen as L = 0.5 m and r = 2 mm.

The thruster has been fired several times using five different input energies (1000 J, 1333 J, 1666 J, 2000 J, 2333 J, 2666 J, 3000 J) with different intensities of applied magnetic field (0 T, 0.21 T, 0.28 T, 0.36 T).

III. Analysis of the data and experimental results

The data acquired with the spectrometer for each energy and for each applied field strength have been averaged and the standard deviation has been calculated showing a good reproducibility of the measurements.

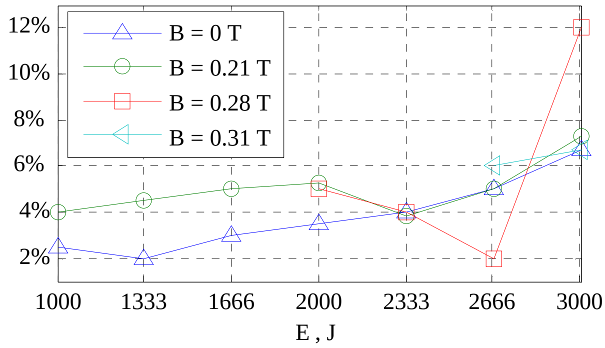

Figure 2. Standard deviation of the measurement for different shot energies and applied field intensities

At all the shot energies the same spectrum lines have been found. One of the acquired spectra is reported below.

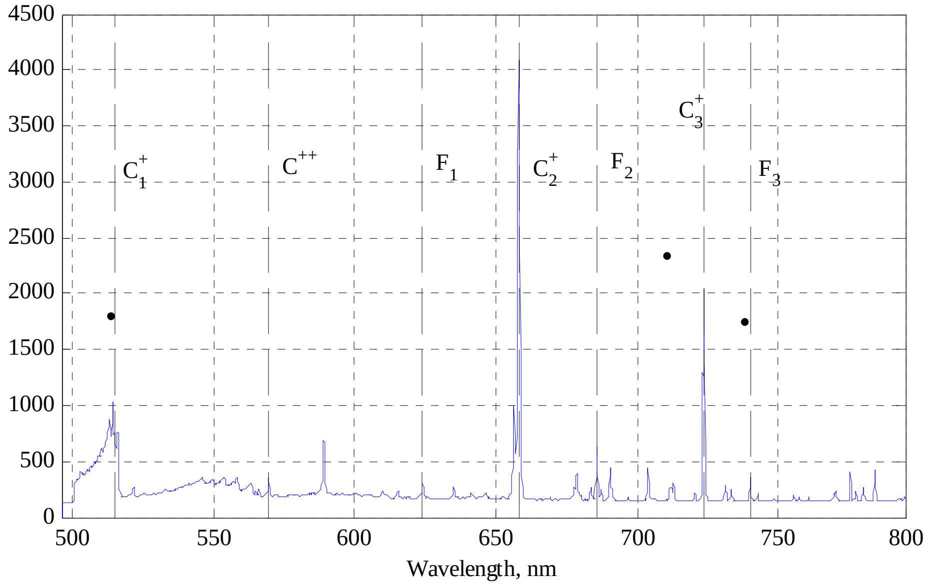

Figure 3. Spectrum of the plasma with the most important lines

Analyzing the spectrum we can find the lines relative to C^{++}, C^+ and F while the lines relative to C, F^+ and F^{++} are out of the scope of the spectrometer.

The lines intensities measured with the spectrometer are directly proportional to the luminance. The luminance is connected with the ion and electron densities and with the electron temperature as shown below where $Q_{i\to j}$, $f_{i\to j}g$ are parameter relative to the transition of a state from the i-th to the j-th ionization level and $\Delta E_{i\to j}$ is the correspondent ionization energy[1] :

$$Lu = \frac{1}{2\pi}\int_0^D n_e n_i Q_{i\to j}\,dx \qquad Q_{i\to j} = \frac{1.6\cdot 10^{-5}}{\Delta E_{i\to j}} f_{i\to j}\, g\cdot e^{\frac{\Delta E_{i\to j}}{T_e}} \tag{1}$$

To calculate the electronic temperature inside the thruster starting from the measurement of the lines intensities we need to formulate some hypotheses on the electronic temperature and density trends along the line of sight from the thruster to the spectrometer and on the ionization level.

Three different hypotheses will be formulated regarding to the temperature and density profiles resulting in the three different analyses described below.

With respect to the ionization level, noting that the plasma generated by this kind of thruster is often characterized by a number density of the order of 10^{20} m^{-3}, the effect of three body collisions can be neglected and so corona equilibrium can be assumed.

The trends of carbon and fluorine ionization with temperature according to the corona equilibrium is reported below

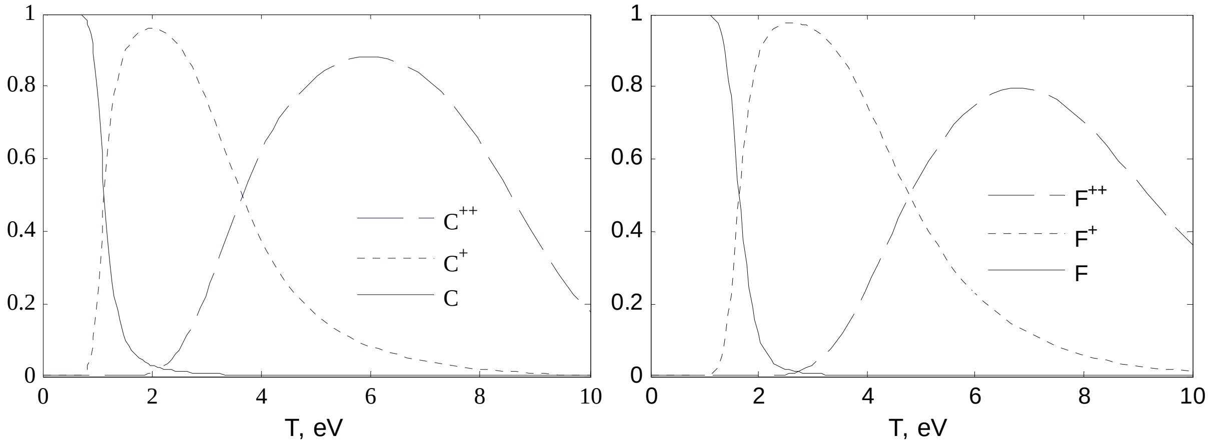

Figure 4. Corona equilibrium concentration of calcium and fluorine ions with temperature

A. First Analysis

In this analysis the easiest assumptions have been made. The electronic temperature is assumed to be constant from the cathode tip down to the spectrometer, the electronic density is also assumed to be constant.

Using these hypotheses in the first of Eq. (1) all the variable can be brought outside the integral sign hence the ratio between two of the measured line intensities can be expressed as

$$\frac{In_1}{In_2} = \frac{Lu_1}{Lu_2} = \frac{n_{i1}(T_e)\ \ Q_{1i\to j}(T_e)}{n_{i2}(T_e)\ \ Q_{2i\to j}(T_e)} \tag{2}$$

If we assume that the ion densities follow everywhere the corona equilibrium these densities are functions only of the electronic temperature hence substituting In_1 and In_2 with the intensities of two lines relative to different species the electronic temperature can be found.

Table 2 – Jet temperature in eV, first analysis							
	1000	1333	1666	2000	2333	2666	3000
C^{++}/C^{+}_{1}	2.9	2.84	2.85	2.78	2.89	3.25	3.3
C^{++}/C^{+}_{2}	2.9	2.8	2.65	2.68	2.68	2.79	2.67
C^{++}/C^{+}_{3}	2.6	2.5	2.42	2.41	2.43	2.5	2.43
C^{++}/F_1	/	2.19	2.21	2.24	2.26	2.29	/
C^{++}/F_2	/	2.31	2.34	2.38	2.41	2.45	2.38
C^{++}/F_3	/	2.31	2.36	2.39	2.42	2.46	2.39
Average	2.8	2.48	2.47	2.48	2.5	2.62	2.2
Average (only C)	2.8	2.71	2.64	2.62	2.66	2.84	2.8

B. Second Analysis

In this analysis the temperature has been assumed to be constant inside the thruster for values of x up to x_{anode} and then to decay exponentially. This exponential decay has been derived from temperature data previously measured by means of Langmuir probes outside the thruster[2, 3] and reported in the figure below.

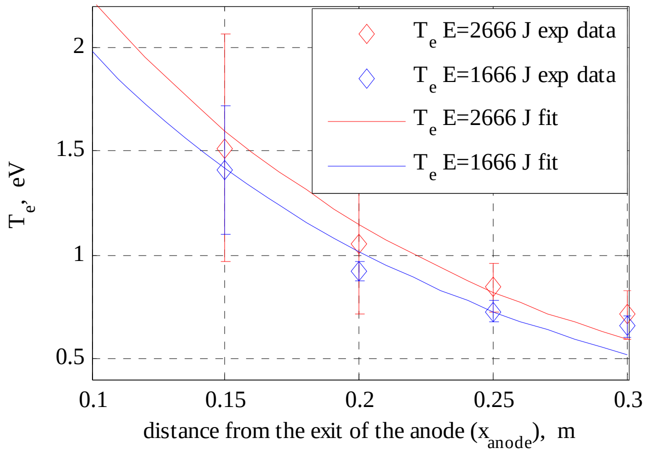

Figure 5. Electronic temperature trend outside the thruster[2, 3]

The electronic temperature can be expressed as

$$\begin{cases} T_e = T_{e\,\max} & x \le x_{anode} \\ T_e = T_{e\,\max}\, e^{-b(x - x_{anode})} & x > x_{anode} \end{cases} \tag{3}$$

where b has been derived from Fig. 4 and has the value of $6.84\ \mathrm{m}^{-1}$. The electron density is still assumed to be constant and the ion density is derived from the corona equilibrium using the local value of the electronic temperature.

In this case the relation between the measured intensities and the electronic temperature is

$$\frac{I_1}{I_2} = \frac{B_1}{B_2} = \frac{\int_0^D n_{i1}(T_e)\, Q_{1i\to j}(T_e)dx}{\int_0^D n_{i1}(T_e)\, Q_{2i\to j}(T_e)\,dx} \tag{4}$$

The calculated values of temperature are in Table 3

Table 3 - Jet temperature in eV, second analysis							
	1000	1333	1666	2000	2333	2666	3000
C^{++}/C^{+}_{1}	2.79	2.84	2.72	2.76	2.78	2.87	2.75
C^{++}/C^{+}_{2}	2.93	2.7	2.68	2.69	2.71	2.82	2.74
C^{++}/C^{+}_{3}	2.71	2.5	2.46	2.46	2.46	2.53	2.46
C^{++}/F_{1}	2.2	2.19	2.22	2.24	2.27	2.3	2.27
C^{++}/F_{2}	2.33	2.31	2.35	2.39	2.42	2.46	2.43
C^{++}/F_{3}	2.34	2.31	2.37	2.41	2.43	2.48	2.44
Average	2.55	2.48	2.47	2.49	2.51	2.48	2.51
Average (only C)	2.81	2.68	2.64	2.63	2.65	2.74	2.65

C. Third Analysis

In this analysis the temperature trend is the same as in the second one. The density is assumed to be constant inside the thruster and to decay exponentially outside it. The exponential decay has been derived from previous Langmuir probe measurements[2, 3] as reported in Fig 5.

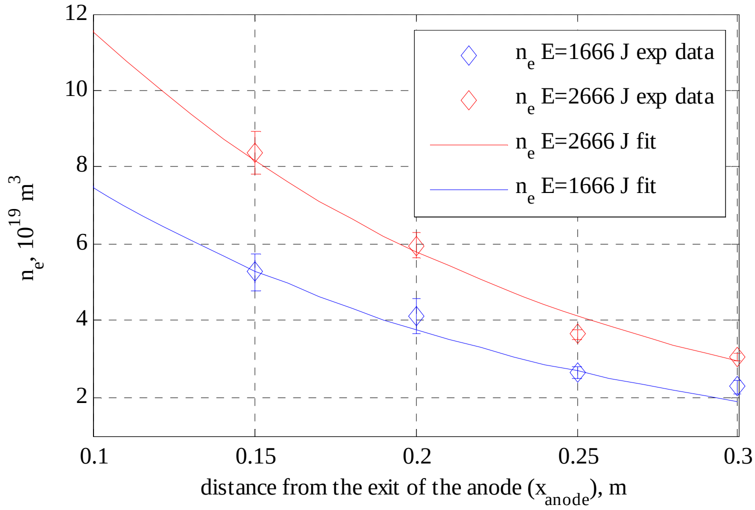

Figure 6. Electronic density trend outside the thruster[2, 3]

hence the electron density can be expressed as

$$\begin{cases} n_e = n_{e\max} & x \le x_{anode} \\ n_e = n_{e\max}\, e^{-b(x-x_{anode})} & x > x_{anode} \end{cases} \tag{5}$$

where the coefficient b has the same value as in Eq. 4, 6.84 m^{-1}. The corona equilibrium hypothesis must now be discussed.

Moving along the x-axis of Fig. 1 we have that the flow velocity goes from zero in the inner part of the thruster up to its exhaust value just outside the anode and then remains more or less constant.

The electronic temperature is assumed to be constant inside the thruster and then to decrease exponentially.

Being the characteristic gasdynamic time inversely proportional to velocity and the ionization characteristic time inversely proportional to temperature, inside and very close to the thruster the gasdynamic time is much bigger than the ionization one, hence in this area the plasma is in ionization equilibrium, whereas far from the thruster the gasdynamic time is smaller than the ionization one because of the low temperature hence in this area the plasma is in a frozen-flow condition.

These two areas must be connected by a non-equilibrium area where the two characteristic times are comparable. For simplicity we will neglect the non-equilibrium area assuming that the flow instantaneously passes from equilibrium to frozen-flow condition.

We assume to have equilibrium inside the thruster (where the temperature is very high) up to a distance of 10 cm from the anode exit (where the temperature is still high enough) and then to suddenly move to a frozen flow regime.

The results obtained with this analysis are in Table 4.

Table 4 - Jet temperature in eV, third analysis

	1000	1333	1666	2000	2333	2666	3000
C^{++}/C^{+}_{1}	3.17	3.04	3.07	3.13	3.16	3.27	3.11
C^{++}/C^{+}_{2}	3.37	3.31	3.02	3.05	3.06	3.2	3.09
C^{++}/C^{+}_{3}	3.07	2.81	2.73	2.73	2.74	2.83	2.73
C^{++}/F_1	3.8	3.73	3.9	4.05	4.2	4.4	4.2
C^{++}/F_2	4.63	4.50	4.76	5.01	5.15	5.5	5.25
C^{++}/F_3	4.67	4.57	4.85	5.13	5.28	5.50	5.34
Average	3.78	3.62	3.72	3.85	3.93	4.12	3.95
Average (only C)	3.2	3.05	2.94	2.97	2.98	3.1	2.97

IV. Experimental results

The electronic temperature has been found plotting the measured luminance ratio, LHS of Eq.(2) and (4), and the calculated one for different values of temperature inside the thruster, RHS of Eq.(2) and (4), and finding the intersection between the two. An example of these plots is presented below

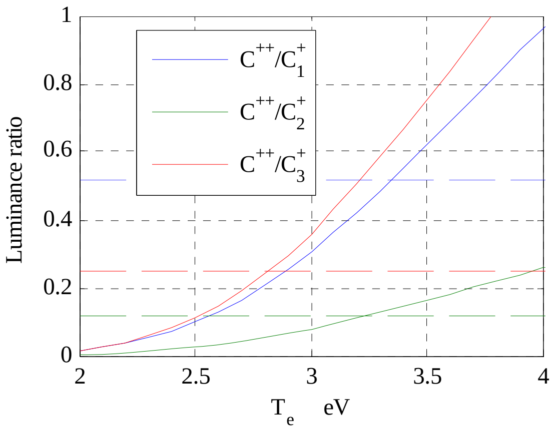

Figure 7. Luminance ratio: - - - - experimental data, —— theoretical data

As can be seen the measuring method has a good sensitivity, in fact a small change in the temperature corresponds to a big change in the measured luminance ratio. For example a temperature change of 0.5 eV will make the luminance ratio of C^{++}/C^{+}_1 moving from 0.25 to 0.5 causing a 100% variation.

The temperatures obtained with applied magnetic field have been calculated only with the third analysis and are reported in Tab. 5-7.

Table 5 - Jet temperature in eV, third analysis, B=0.21

	1000	1333	1666	2000	2333	2666	3000
C^{++}/C^{+}_1	3.17	3	3.3	3.26	3	3.3	3.1
C^{++}/C^{+}_2	3.04	2.9	3.09	3.11	2.97	3.15	2.96
C^{++}/C^{+}_3	2.74	2.64	2.78	2.81	2.68	2.81	2.64
C^{++}/F_1	2.26	2.28	2.37	2.36	2.23	2.39	2.33
C^{++}/F_2	2.5	2.46	2.58	2.58	2.5	2.62	2.53
C^{++}/F_3	2.47	2.47	2.59	2.58	2.51	2.63	2.54
Average	2.6	2.51	2.5	2.62	2.74	2.44	2.77
Average (only C)	2.98	2.84	3.05	3.06	2.88	3.08	2.9

Table 6 - Jet temperature in eV, third analysis, B=0.28

	2000	2333	2666	3000
C^{++}/C^{+}_1	2.96	2.98	2.67	3.16
C^{++}/C^{+}_2	2.93	3.14	2.64	3.13
C^{++}/C^{+}_3	2.65	2.75	2.4	2.76
C^{++}/F_1	2.23	2.37	2.14	2.37
C^{++}/F_2	2.48	2.58	2.37	2.58
C^{++}/F_3	2.47	2.6	2.39	2.6
Average	2.2	2.74	2.44	2.77
Average (only C)	2.84	2.95	2.58	3.01

Table 7 - Jet temperature in eV, third analysis, B=0.36		
	2666	3000
C^{++}/C^{+}_{1}	3.05	3.02
C^{++}/C^{+}_{2}	2.97	2.77
C^{++}/C^{+}_{3}	2.66	2.48
C^{++}/F_{1}	4.08	3.7
C^{++}/F_{2}	5.83	5.66
C^{++}/F_{3}	6.14	5.76
Average	4.12	3.9
Average (only C)	2.89	2.75

Some of the temperature values are not present because the thruster presented a threshold value of the applied field over which it does not work. These threshold values of applied field are presented and discussed in Ref 4.

The temperature can be determined as the average between all the luminance ratios or as the average of only those relative to carbon ions.

Looking at the tables it can be noted how the temperature values relative to the luminance ratios between carbon ions are quite often in agreement between them showing small and gradual variation with the application of a magnetic field. Instead the temperatures relative to calcium and fluorine ions luminance ratios tend to show a more random behaviour. For this reason to obtain the best estimate the temperature as been calculated using the average of the values obtained only from the luminance ratios relative to carbon ions.

The temperatures so obtained are in agreement with previous measurements showing values close to 3 eV that have small variation with the shot energy. This can be explain noting that the MPD used in this work is a solid propellant MPD hence the mass flow rate is directly proportional to power, for this reason the specific power is almost constant with input power hence small temperature variations should be expected.

A plot with the temperature trend with specific power is reported below

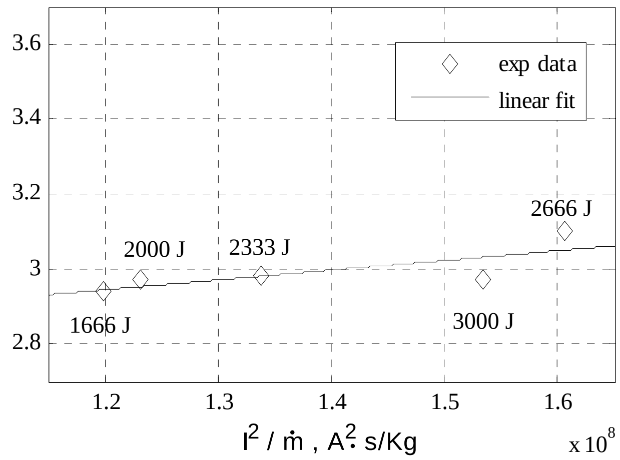

Figure 8. Trend of temperature with specific power

The measured temperatures also show almost no sensitivity to the application of a magnetic field confirming one of the hypotheses stated by one of the author in Ref. 5.

Using these temperatures the overall ionization fraction can be obtained from the corona equilibrium as

$$\alpha = \frac{2\,(n_{C^+} + n_{C^{++}}) + 4\,(n_{F^+} + n_{F^{++}})}{6} \tag{6}$$

The results are reported below

Table 8 – Ionization fraction α at various energies and different values of applied field							
Energy	1000	1333	1666	2000	2333	2666	3000
B=0	1.13	1.1	1.07	1.08	1.08	1.11	1.08
B=0.21	1.08	1.06	1.10	1.10	1.06	1.10	1.06
B=0.35	1.06	1.03	1.04	1.06	1.08	1	1.09
B=0.5	1.01	1.09	1.04	1.02	1.03	1.06	1.03

As can be seen the ionization fraction is almost constant and equal to one and this is in qualitative agreement with the ξ parameter (ratio between the current and the complete ionization current) that for this thruster is around 0.8 and shows small variation with energy [4].

V. Theoretical expectations

The temperature of the jet can be inferred from the knowledge of the thrust, current and mass flow rate of the thruster assuming that the thrust produced by the MPD is purely electromagnetic.

The mass flow rate at the exit of the nozzle is

$$\dot{m} = m_i\, n\, v\, A \tag{6}$$

the temperature can be expressed as

$$p = 2\, n\, k_b\, T_e \tag{7}$$

now deriving the particle density from Eq.(6) and substituting in Eq.(7) and remembering that $v = \frac{F}{\dot{m}}$ and $p = \frac{\mu I^2}{8\pi}\frac{1}{A}$ we can finally obtain the temperature as a function of thrust mass flow rate and current.

$$T_e = \frac{\mu I^2}{16\pi}\frac{m_i\, F}{\dot{m}^2}\frac{1}{k_b} \tag{8}$$

Using the mass flow rate, current and thrust for the MIRA thruster[4] including the relative uncertainties on these measurements the average, maximum and minimum temperatures obtained are

Table 9. Comparison between experimental and expected values					
Energy	1666 J	2000 J	2333 J	2666 J	3000 J
T_{exp}	2.94 eV	2.97 eV	2.99 eV	3.10 eV	2.98 eV
$T_{th\ min}$	1.52 eV	1.84 eV	1.75 eV	2.29 eV	2.09 eV
T_{th}	2.07 eV	2.30 eV	2.69 eV	3.85 eV	3.38 eV
$T_{th\ max}$	2.72 eV	2.83 eV	3.86 eV	5.85 eV	5 eV

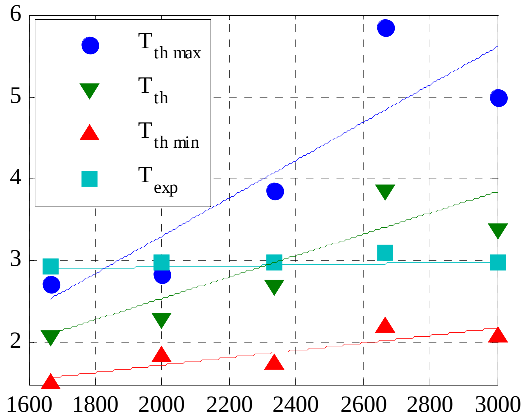

Figure 9. Comparison between experimental and theoretical values of the temperature

As can be seen from Fig. 8 the calculated temperature are quite sensible to the variation in the measured thrust and current; the experimental temperature values lie between the maximum and minimum calculated values and close to the mean calculated values showing a satisfactory agreement.

VI. Conclusions and future works

Using spectroscopic measurement the temperature inside an MPD thruster has been measured with and without the application of an external magnetic field. The measured temperatures are consistent with previous measurements and if compared to the expected values calculated using a simplified formula show a satisfactory agreement.

The temperatures do not vary sensibly with the application of a magnetic field confirming one of the hypotheses stated by one of the authors in Ref. 5.

The measured values of temperature correspond to a high ionization level very close to unity in agreement with the current over complete-ionization-current ratios calculated in Ref 4.

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