Operation of an MPD Thruster with a Type B Cathode[*†]

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The paper deals with the results of an experimental investigation on the operation of a pulsed, quasi-steady, gas-fed MPD thruster, equipped with an artificially heated type B dispenser cathode. After an activation procedure, consisting of maintaining the cathode temperature as high as 1500 K for about thirty minutes at a vessel pressure of 10^{-4} torr, a surface work function of 2.6 eV at 1200 K has been measured. Then the thruster has operated with the type B cathode with 500 mg/s of argon, different current levels up to 4.7 kA and a cathode temperature of 1200 K. Measurements show that for currents above a threshold the electrical characteristics of the thruster with the dispenser cathode is lower than with a W cathode of identical geometry. This occurrence can be explained by theoretical results of a recently developed model of the cathode spot ignition phenomenon: the low value of the dispenser cathode work function has allowed the activation of more spots and consequently a more uniform current distribution than on the tungsten cathode, with beneficial effects on thruster electrical characteristics.

Introduction

MPD thrusters are favorably considered for low power, auxiliary applications, as well as for medium to high power (from tens of kW to MWs), primary missions, ranging from orbit-raising of large satellites to cargo interplanetary transfer. For this last class of missions MPD thrusters represent almost the unique electric propulsion option, provided a specific impulse of 4000-6000 seconds, a thrust efficiency of 0.6-0.75 and a lifetime ranging from 5 to 10 thousands hours are exhibited. Cathode operation can have a great impact on thruster performance: cathode depletion due to highly erosive current emission mechanisms (spotty arc attachment), occurring at low cathode temperature and/or cathode material evaporation, occurring at high cathode temperature is generally considered a critical issue, limiting the thruster lifetime and in general causing performance degradation.

Geometrical configuration, material and temperature management represent the crucial aspects for the development of efficient and long-life cathodes. Hollow cathodes and multiple hollow cathodes have shown promising performance with respect to traditional cylindrical cathodes [1-3]. Moreover, the adoption of low work function tungsten alloys (thoriated, bariated, lantaniated tungsten) together with a cathode heating system capable of heating and controlling cathode temperature seems to prolong significantly the cathode lifetime, also in a pulsed, low power application [4].

Overview on cathode phenomena study at Centrospazio

The need to begin a theoretical and experimental activity aimed at investigating cathode phenomena in an MPD thruster originates from test results obtained at Centrospazio on pulsed quasi-steady, gas-fed MPD

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thruster with cathode heating system [5-8]. Thruster operation with a hot 2% thoriated tungsten cathode showed several benefits with respect to operation without cathode heating:

- a lower electric characteristics for current above the full ionization threshold [6, 7];
- a reduction of the plasma potential drop in the cathode region [7, 8];
- a more uniform current distribution [8]; cathode regions upstream the tip resulted more interested by the arc attachment than with the cold cathode, where the arc mainly attached on the tip;
- a more uniform, less damaging erosion all over the cathode surface [8].

Current density measured on the cathode tip region was consistent with the hypothesis of a field-enhanced thermionic emission from the surface, provided that a Th atoms mono-layer forms on the surface, implying a work function reduction to about 2.7 eV. Theoretical considerations showed the balance between Th diffusion from the interior and Th evaporation from the surface allowed a complete coverage to be obtained during experiments with cathode heating [4]. Moreover theoretical explanations of the beneficial effect of cathode heating on the other cathode regions were advanced [9].

Then a new experimental activity has been planned [10] in order to study thruster behavior with different cathodes, identical in geometry but made of different materials. Cathode materials and dimension were selected to let the entire thruster current (or a large fraction at least) to be emitted in a field-enhanced thermionic regime, all over cathode surface. The following materials were chosen: tungsten, 2% thoriated tungsten and porous tungsten (porosity of 20%) impregnated with a 5:3:2 BaO – CaO - Al_2O_3 compound (emitters of this last material are known as type B dispenser cathodes). The tungsten cathode was intended as the benchmark configuration: its performance has taken as a term of comparison for the other two electrodes.

Since these two electrodes need an activation procedure in order to become good thermionic emitters, a new technique was set up for measuring the effective work function value with an error lower than 5%.

This technique has been successfully verified during a first test campaign [11]: the work function has been measured for the W cathode and for the same cathode coated with a low work function compound, after activation. In both cases results agree with theory. Due to the coating detachment after few shots, thruster operation with the coated cathode at a temperature of 1200 K have not revealed any performance improvement with respect to W cathode operation.

In the same time a theoretical study has been carried out on the spot emission mechanism [12]. A numerical model has been developed on thermoelectric phenomena encountered by microprotrusions on the cathode surface immediately before an arc discharge. Results indicate that the surface work function has a crucial role on these phenomena: spot activation in correspondence of a microprotrusion is eased by lowering the work function. Proceeding by deduction: the lesser the surface work function is, more spots are active on the cathode surface; the current attaches in more and more points until it is spread uniformly on the surface when the work function reaches the value that allows all the current to be emitted by thermionic effect.

This paper describes the experimental activity concerning the type B dispenser cathode. For the activation, the procedure reported in [13] has been reproduced: it consists in heating the cathode to about 1500 K for one hour, at a vessel pressure of $2x10^{-9}$ torr. This last requirement has not been satisfied in this context because of performance limits of the pumping system.

After activation and according to previous study [14], the cathode should have an effective work function of 2.17 eV at 1500 K. Assuming during thruster operation an electric field of $5x10^7$ V/m on the cathode surface, at 1500 K the type B cathode would be able to emit more than 200 A/cm^2 in the thermionic regime, enhanced by Schottky effect.

Experimental Apparatus and Test Equipment

The experimental apparatus (Fig. 1) is a gas-fed, multi-MW, self-field MPD thruster, operating in a pulsed, quasi-steady mode (for a detailed description see [15]). The deoxidized copper anode is cylindrical with an inner diameter of 100 mm. The cathode consists of a short cylindrical part followed by a semispherical tip, 13 mm in radius, for a nominal emitting surface of 20.4 cm^2. The cathode is equipped with an arc heating system [10], that allows the cathode surface temperature to be raised up to 2000 K before each thruster shot. The backplate is made of boron nitride and hosts two series of gas injectors: one at the cathode root and one at the middle radius between the electrodes. Gas injection is provided by a solenoid valve, capable of producing quasi-steady gas pulses about 50 ms long. The valve is backed by a reservoir about 1000 cc in volume to keep the back pressure fairly constant during the pulse. This allows a long plateau with a constant mass flow rate to be obtained during each pulse.

Electric energy for the MPD discharge is supplied by a Pulse Forming Network (PFN), capable of producing quasi-steady current pulses from 1 to 5 ms long and a maximum amplitude from 30 kA to 5 kA respectively. To perform the discharge at steady mass flow conditions, the arc is activated by an ignitron, delayed of few milliseconds with respect to the valve opening. The delay duration was determined during a previous gas feeding system calibration.

The test equipment is based on a fibre-glass vacuum chamber 0.5 m^3 in volume, equipped with a diffusion pump capable of an ultimate pressure of $4x10^{-5}$ mbar.

Anode and cathode voltages are measured by two high voltage probes and recorded by an oscilloscope HP 5185, while the current is derived by the signal from a Rogowsky coil and recorded by a transient recorder Tektronix TDS 220.

For the dispenser cathode, surface temperature is measured by a standard type K thermocouple. The measurement error due to the calibration uncertainty (0.75%) and the non proper use (the thermocouple joining touched the cathode surface virtually in a point) has been estimated within 1%. The measurement range extends up to 1530 K.

For the W cathode, an home-made, tungsten-rhenium thermocouple has been adopted. The thermocouple consists of two wires 0.254 mm in dia (0.01"), one made of W - 5% Re and the other of W - 26% Re alloy. The wires are inserted in a two-bores alumina stick 180 mm long, that keeps the wires spaced at 2 mm from each other and interfaces the thermocouple with the moving device. On one side, the wire edges are not welded and are exposed about 5 mm out of the stick. On the other side, the wires are connected to a compensation cable, extending outside the vacuum chamber. In the measuring position, the TC wires are in touch with cathode surface; the measurement error has been estimated equal to 1%.

The thermocouple moving device [10] allows the thermocouple to be moved from the measuring position to a safe position, when the cathode has reached the operation temperature, just before a firing. During work function measurements, the thermocouple was placed in its measuring position during the entire test.

The electrical circuit for thermionic current measurement is shown in fig. 2 and described accurately in a previous work [10]. The thermionic current is directly derived from measuring the voltage signal across the 50 Ω resistance.

An AT-MIO-16E-2 acquisition board has been used for both temperature and thermionic current acquisition. Temperature channel has been set with a range of (-50, +50) mV with a resolution of 24 μV, while for current channel the measurement range and by consequence resolution must be changed periodically, since the thermionic current is expected to vary by order of magnitude, during cathode activation experiment.

Results and discussion

Type B cathode activation

The cathode has been unpacked and assembled to the thruster, already mounted in the vacuum chamber ready to be evacuated, in order to minimize the exposure to the atmosphere.

After reaching the final pressure, the activation procedure has started: the heating system has been turned on and temperature and thermionic current have been monitored at a rate of 2 Hz. During activation, thank pressure has been almost constant around the value of $1x10^{-5}$ mbar.

The first heating process has taken less than 10 minutes and the corresponding data are shown in fig. 3. The knee in the temperature curve at about 1100 K corresponds to a decrease of the heating power, while the instant of shut off is immediately followed by an abrupt descent of the curve. The thermionic current curve presents some intervals of almost constant value despite the increasing temperature; this could indicate that the surface is being undertaken any physical or chemical transformation, resulting in a slight increase in the work function value that cancels out the temperature effect. When temperature approaches the value of 1500 K, corresponding to the activation temperature, the current starts again to increase and rapidly reaches the value of 20 mA, corresponding to the limit of the data acquisition range. Then the heating system has been shut off. Current data gathered during the cooling period are affected by strong perturbation probably due to some electromagnetic interference at the moment of shutting off.

The second heating process has been much longer: the activation temperature has been reached in less than 3 minutes and has been kept almost constant for about 25 minutes.

Temperature and current data have been reported in fig. 4. Despite a constant temperature, the thermionic current continuously increases at a rate almost constant even during the last minutes, when temperature is slightly decreasing. This occurrence seems to indicate that cathode activation is in progress and the surface work function is decreasing by effect of the formation of a Ba atoms coverage, although, as shown in the following, the work function decrement is of the same order of magnitude of the error.

Unfortunately after about 27 minutes from the beginning of the heating process, the BN insulator between the electrodes has broken, making the experiment to be interrupted. Data have continued to be recorded during cathode cooling and as can be seen from fig. 5 the thermionic current has continued to increase until the maximum allowed by the acquisition board capability (100 mA). This means that activation has continued also during the first 30 seconds of the cooling time, as could be expected considering that Ba atoms diffusion does not stop abruptly. Fig. 6 shows the relation between the work function and the temperature both as resulted from the experiment and as suggested by Rittner [14] for a type B cathode fully activated. About the experimental curve, it has been calculated considering temperature and current values recorded from the beginning of the steady temperature phase to the first 30 seconds of the cooling phase. The length of the vertical segment with abscissa T=1534 K corresponds to the decrease of the surface work function due to the activation process and it is equals to 0.11 eV. At 1100 K the work function value determined experimentally is 2.33 ,against the theoretical value of 2.04.

Fig. 7 reports the work function versus temperature curve for both the tungsten cathode as determined in a past experimental activity and the dispenser cathode. Comparison confirms both the effectiveness of the work function measurement technique and a certain activation degree of the dispenser cathode has been reached.

Immediately after the end of the experiment the cathode has been vacuum sealed and maintained in that condition for two months until the thruster has been fixed.

Uncertainty analysis

Considering the experimental procedure adopted for the work function calculation, the uncertainty on its value $j_{\%}$ is given by:

$$\varphi_{\%} = \sqrt{\left(\frac{I_{\%}}{ln\dfrac{I}{AST^2}}\right)^2 + \left(\frac{S_{\%}}{ln\dfrac{I}{AST^2}}\right)^2 + \left(\frac{T_{\%}\left(ln\dfrac{I}{AST^2} - 2\right)}{ln\dfrac{I}{AST^2}}\right)^2}$$

Since $|\ln(I/AST^2)|$ is >10 for the test condition considered, the effect on $j_{\%}$ due to the uncertainties of I and S are attenuated by a factor greater than 10, while the temperature uncertainty propagates to $j_{\%}$ without practically any scale factor.

Resolution adopted for thermionic current measurement is so high to neglect the current uncertainty contribution. Error in determining the emitting surface area can be as high as 100%, since the real surface can be as twice as the nominal surface, by effect of the surface finishing. In this case, although attenuated, the error on the calculated work function due to $S_{\%}$ is not negligible; in the cathode activation experiment it has been evaluated equal to 3.9%. The uncertainty of T deriving from the error measurement can be considered equal to 1% for both TC types. Taking into account the not complete uniformity of temperature on the cathode surface (2.7% from thermal analysis [10]), the overall temperature uncertainty $T_{\%}$ has been safely assumed equal to 3.0%. According to the above equation, the error on the calculated work function is 5%.

Thruster operation

Before proceeding with the electrical characteristics measurement for the thruster operating with the dispenser cathode, cathode contamination has been verified by measuring the work function. Indeed during the first heating process, at a cathode temperature of 1200 K, the measured thermionic current was much lower than expected for a work function value of 2.6 eV as measured at the end of activation. According to some literature [16] on the reactivation techniques, some very rapid heating processes to a maximum temperature of 1500 K have been performed.

In this way the cathode has been reactivated as shown by fig. 8, referring to the last heating process: at a temperature of 1200 K, the calculated work function is 2.7 eV. In order to avoid excessive thermal stress of the thruster, cathode activation has not been completed.

During the electrical characteristics measurement, the cathode has operated at a temperature of 1200 K, while the work function has kept constant at a value of 2.6-2.7 eV, as verified with dedicated measurements between shots.

The thruster has been fed with argon at a mass flow rate of 0.5 g/s, totally injected at the cathode root, and supplied by electric pulses 2.5 ms in length, with current level ranging from 2 kA to 5kA, slightly above the estimated full ionization current (4.7 kA, considering a thrust coefficient of 2x10^{-7} N/A^2). The partially activated cathode is able to emit in the thermionic regime an amount of current absolutely negligible with respect to the total current.

A total of 16 shots have been performed with the dispenser cathode and results in terms of electrical characteristics have been reported in fig. 9, while fig. 10 shows typical current and voltage signals.

Data points in fig. 9 have been obtained averaging current and voltage values in a time interval equal to one tenth of the pulse length, centred at the middle of pulse; the error bars represent the standard deviation.

In a preceding experimental campaign the thruster has operated with the W cathode. Operating conditions in terms of propellant, electrical pulse duration and swept current range have been the same as for tests with the dispenser cathode.

A series of 14 shots have been performed without cathode heating. Successively the cathode has been polished in order to bring its surface back to the original state and a minor number of shots have been performed, heating the cathode at a temperature of 2000 K and selecting just two current levels.

Results in terms of V-I plot are shown in fig. 11 for both cold and hot operations.

Electric characteristics comparison

Fig. 12 shows the electric characteristics for the thruster operating with the partially activated dispenser cathode and the W cathode with and without cathode heating. Except for data referring to the hot W cathode, each series of points has been fitted to a line, in the current range lying under the full ionization current value I_f.

Points referring to the hot W cathode lie above the electric characteristics of the thruster with the same cathode, but operating at ambient temperature. The difference in the total voltage drop between hot and cold W cathodes seems almost the same for the two current levels investigated. Probably deposition onto the anode surface of material evaporated from hot surfaces, as the cathode and the BN backplate, increases the resistance for the current passage throughout the anode surface with respect to thruster operation without cathode heating. No attempts have been made to quantify this resistance increase and the associated voltage drop, while the effect of the increase in metal resistivity due to high temperatures can be considered almost negligible (1 V).

Since data referring to the hot W cathode are limited to just two current values, the above considerations are not conclusive.

On the contrary, tests on the dispenser cathode have been as extensive as those on the cold W electrode and the comparison is surely more reliable. At the lowest current levels, points referring to the dispenser cathode are above the electric characteristics for the thruster operating with the cold W cathode, while the opposite seems to verify approaching I_f. Looking to the equations of the fitting lines the voltage drop term independent from the current is greater for the dispenser cathode than for W cathode. The fact that the V-I curve for the dispenser cathode intercepts that for the cold W cathode (and keeps completely under that for the hot W cathode) means that the current-dependent voltage term is lower for the first than for the second cathode. This difference can not be attributed to the cathode operating high temperature, as results with the hot W cathode shown, but electrode material properties must have played some important role.

The current-dependent voltage term especially accounts for resistive losses in the electrode region; it is reasonable to suppose that current distribution on the electrodes surfaces, especially the cathode, has an effect in reducing or increasing these losses.

Although partially activated, the surface work function of the dispenser cathode is sensibly minor than that of the W cathode and this fact can have facilitated a more uniform arc attachment on the first than on the second cathode, as suggested by theoretical results from the spot ignition model. As macroscopic effect the slope of the V-I curve for the thruster mounting the type B cathode is less than that of the thruster with the conventional cathode.

Surface Observations

After operation, both cathodes have been observed by a JVC TK-S350 video camera. As an example of the type of surface damage encountered by the two cathodes, Fig. 13 shows the image of a same zone on the semispherical tip. In fact cathodes have not operated exactly at the same conditions, that say equal number of shots for the same current values, but the total flowed charge is about 70 C for both electrodes. The images reveal that also the dispenser cathode has worked in an spotty emission regime: spots are spread all over the surface and, with few exceptions, their dimension is comparable to the dimension of the W matrix pores (10 μm). On the contrary the W cathode surface presents the trace left by a large spot, while the rest of the surface has not been practically interested by arc attachment.

Concluding remarks

A type B dispenser cathode has been designed, manufactured and tested on a PQS MPD thruster at Centrospazio. A partial activation of the impregnated cathode has been reached and a surface work function of 2.6-2.7 eV at 1200 K has been obtained, against the value of 2.1 eV for a complete activation. This result has been obtained in spite of a tank ultimate pressure of $1\text{x}10^{-5}$ mbar, higher than that suggested by others for a correct cathode activation.

Moreover the effectiveness of the reactivation procedure, consisting in a series of rapid heating cycles to 1500 K, has been successfully verified.

With an incomplete activation of the dispenser cathode, thermionic current emission during thruster operation is negligible; on the contrary with a well-activated cathode the thermionic current could be a considerable fraction of the total thruster current.

Anyway thruster performance with the dispenser cathode seems to improve with respect to thruster operation with a cold W cathode, in terms of electric characteristics and for current values approaching the full ionization current. This improvement is not directly caused by the cathode high temperature, that, on the contrary, seems to shift the electric characteristics toward higher voltages, as partially verified.

Results from spot ignition model suggest an interpretation: the benefit induced by operating with the dispenser cathode is due to a more uniform current distribution on its surface than on the W cathode, due to its lower work function. This hypothesis seems to be supported by surface observations of both the electrodes after firings.

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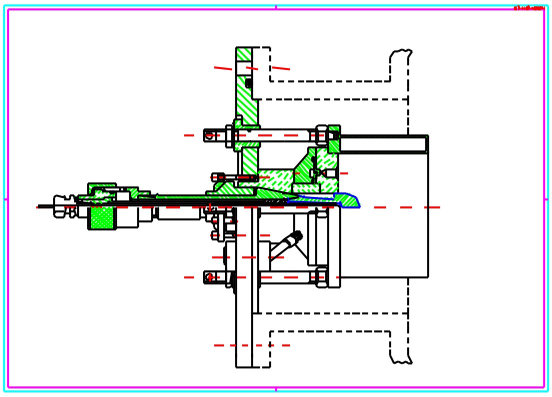

Figure 1 - Experimental apparatus.

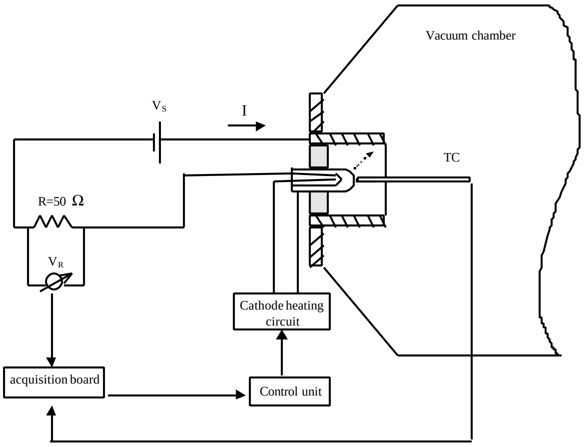

Figure 2 - Work function measurement circuit.

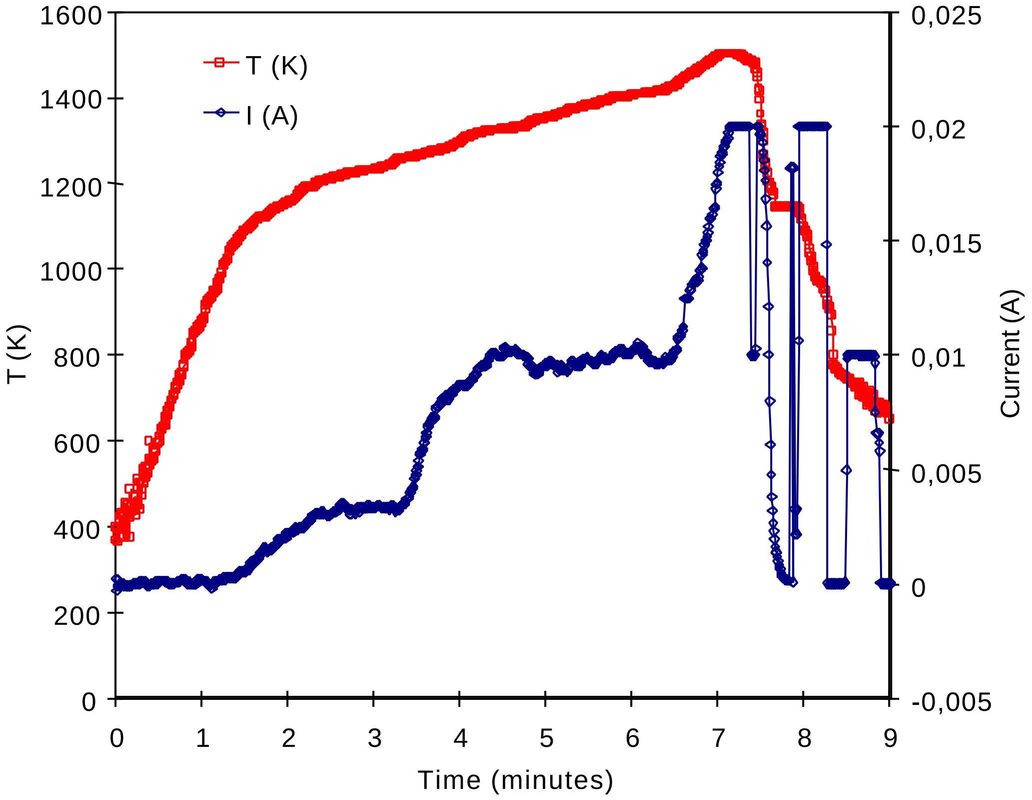

Figure 3 - Temperature and thermionic current versus time; first heating.

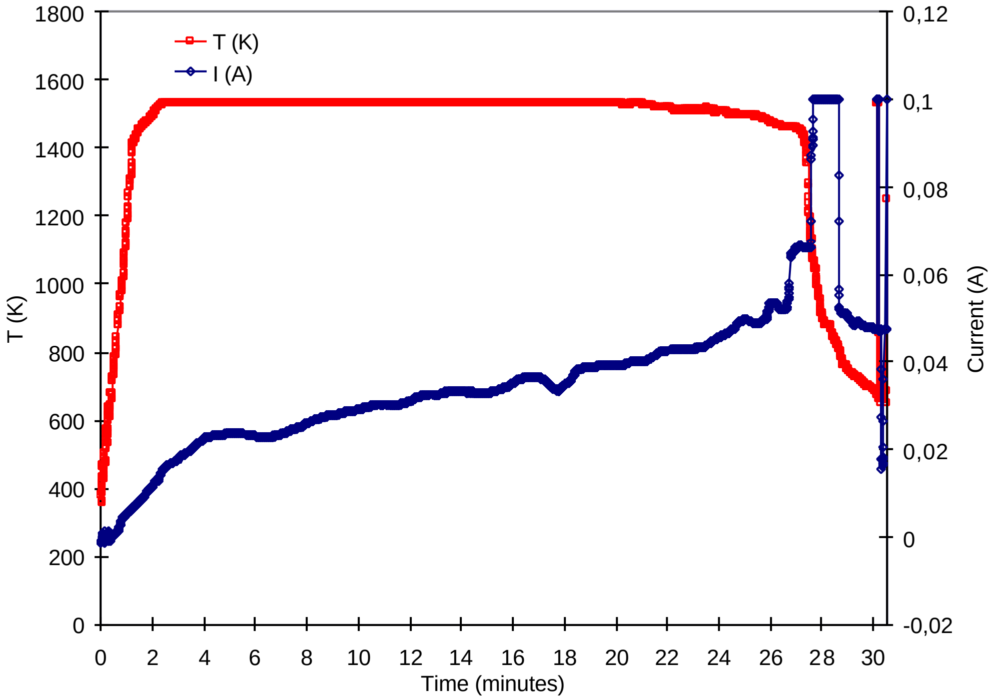

Figure 4 - Temperature and thermionic current versus time; second heating.

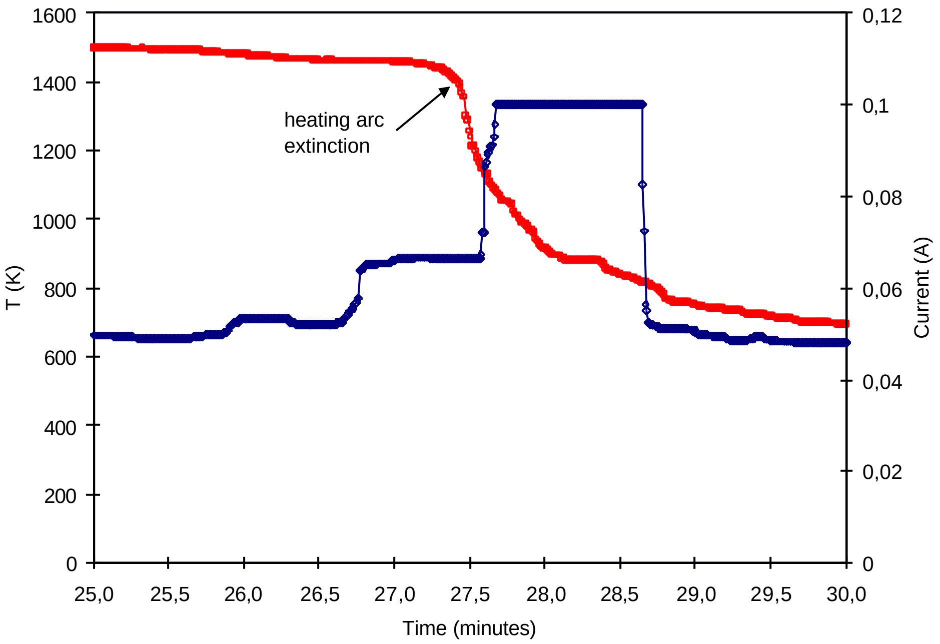

Figure 5 - Temperature and thermionic current versus time; second heating, zoom.

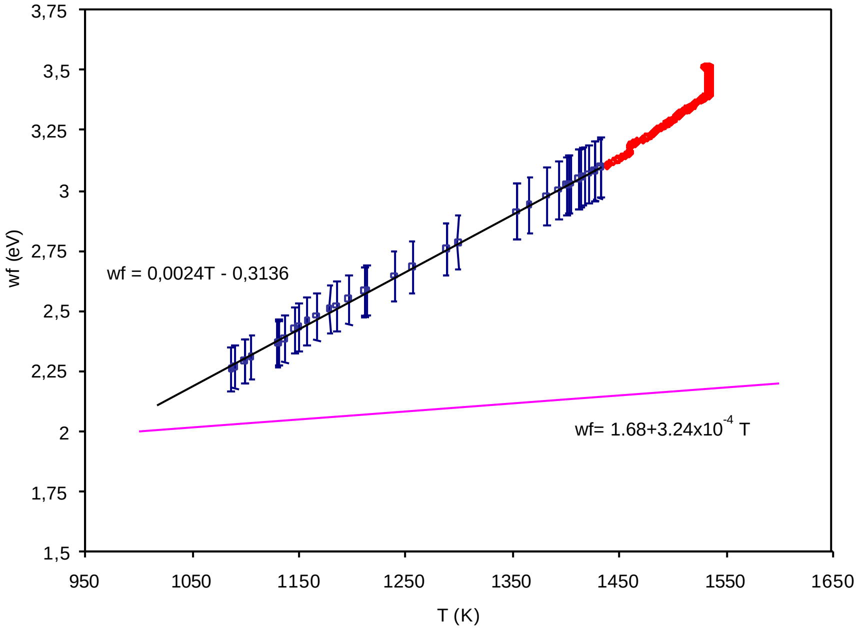

Figure 6 - Theoretical and experimental work function of the type B cathode.

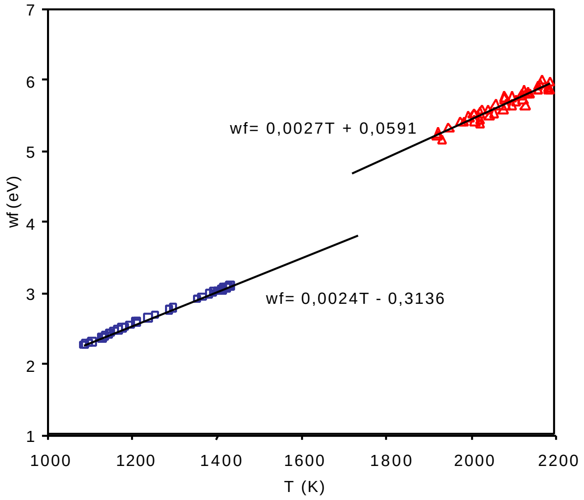

Figure 7 - Experimental work function of the type B cathode (square) and of the W cathode (triangle).

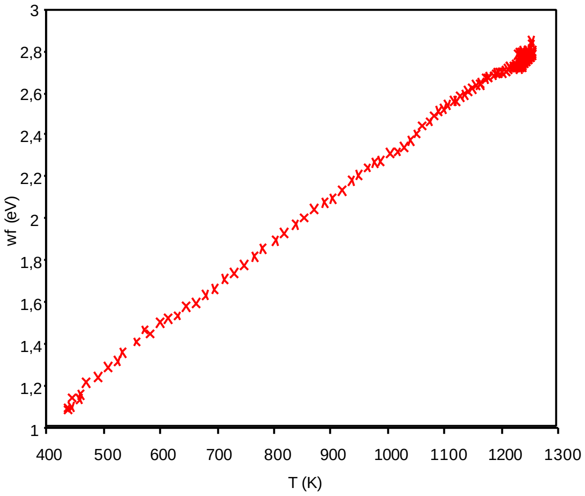

Figure 8 - Type B cathode work function after reactivation.

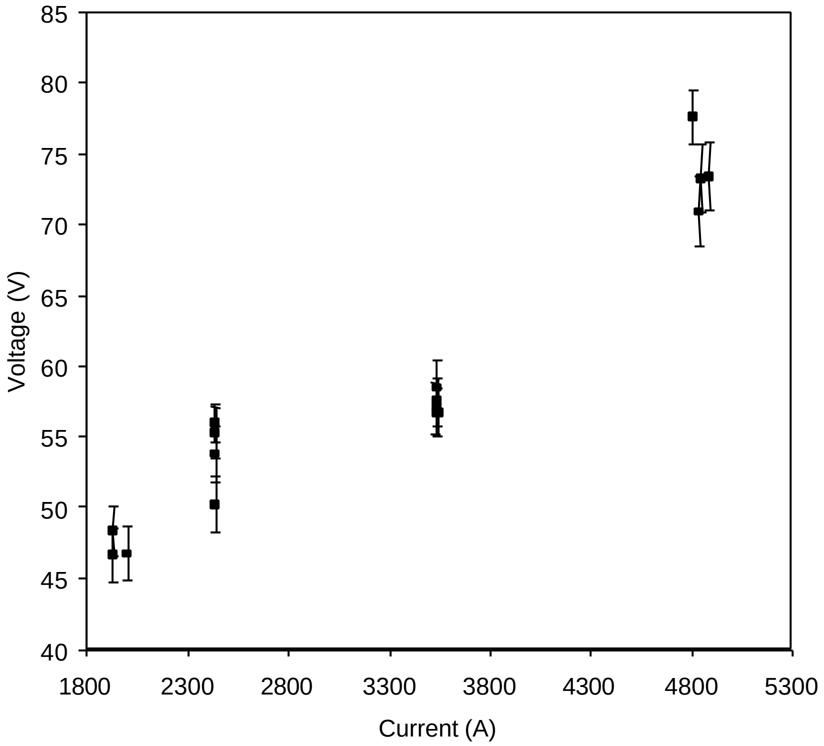

Figure 9 - Electric characteristics of the thruster with the type B cathode.

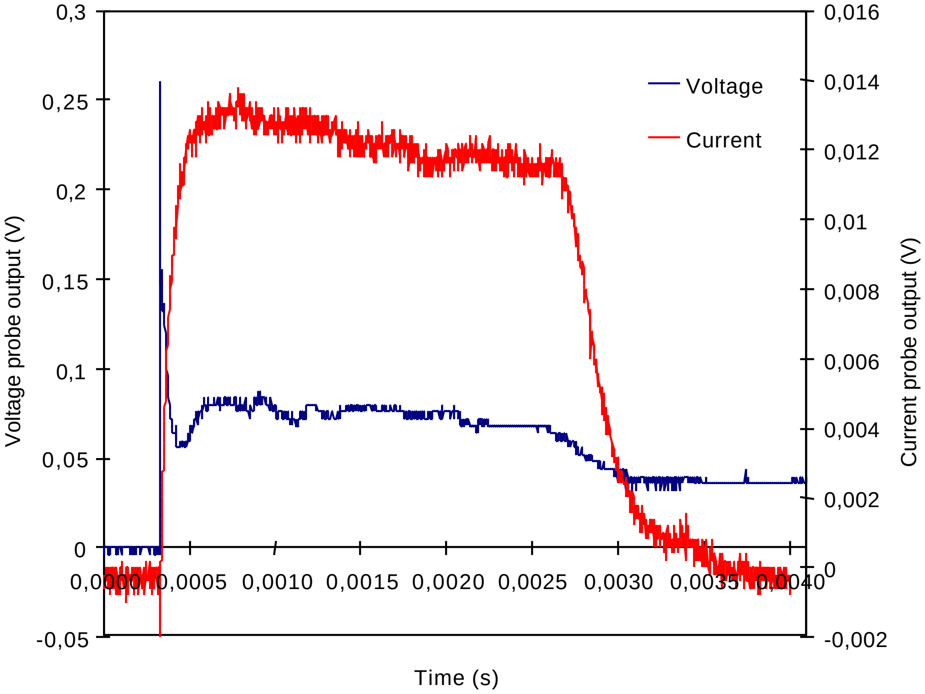

Figure 10 - Typical current and voltage signals.

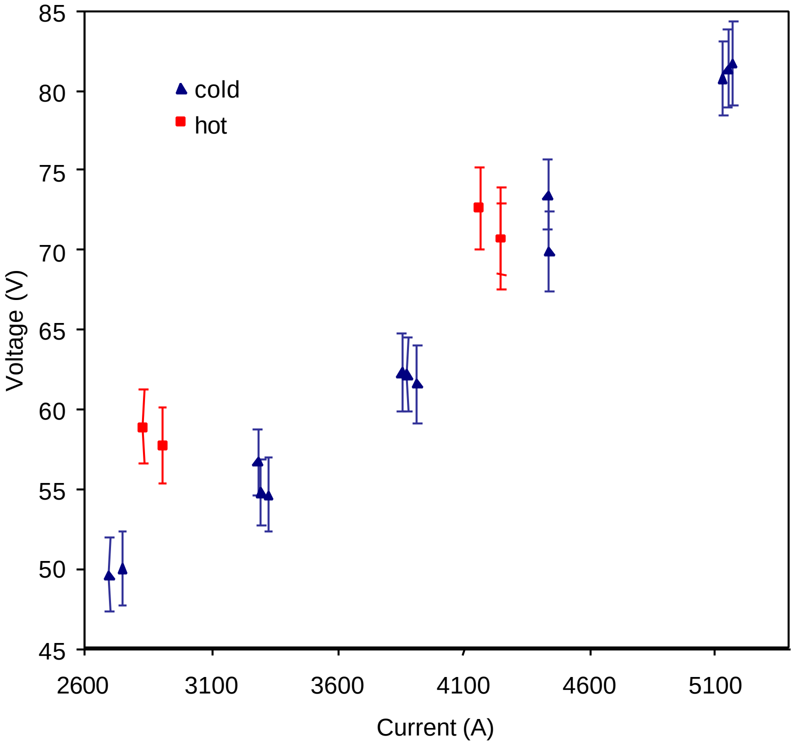

Figure 11 - Electric characteristics of the thruster with the W cathode.

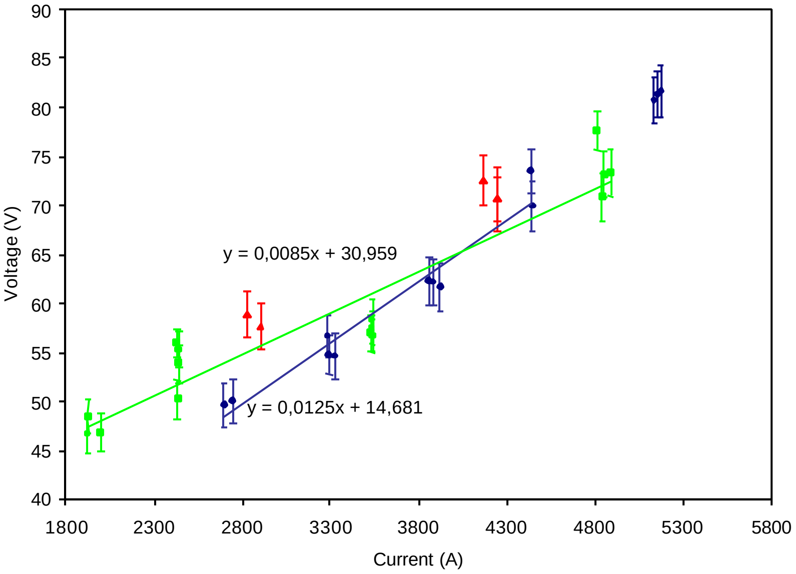

Figure 12 - Thruster electric characteristics; comparison for different cathode operation conditions: dispenser cathode (squares), hot W cathode (triangles), cold W cathode (circles).

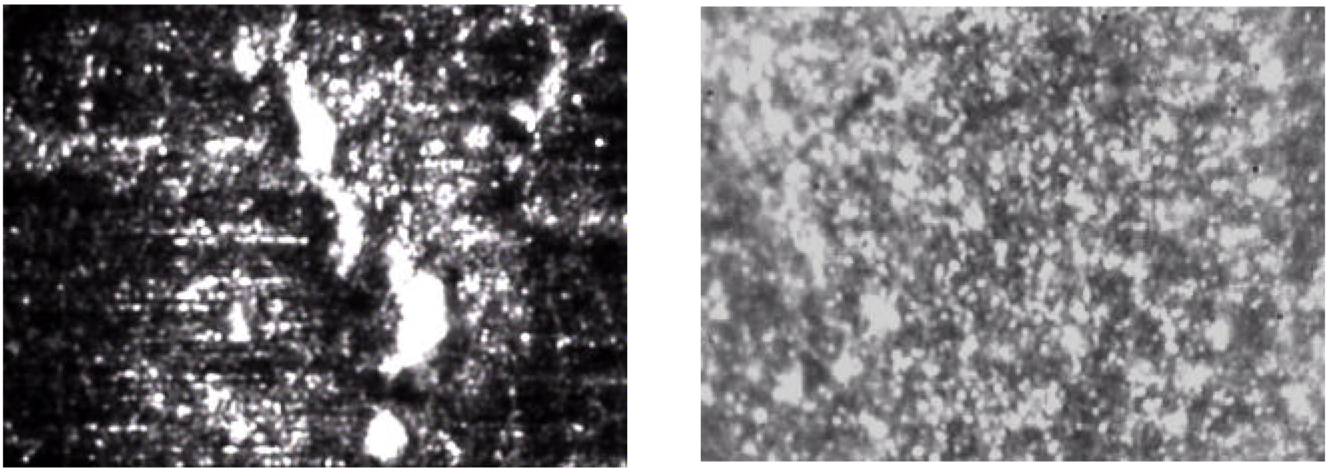

Figure 13 - Surface damage of the cold W cathode (left) and of the type B cathode (right) after shots; the base of each image corresponds to 1.2 mm.