Plasma characterization in a VAT plume by optical emission spectroscopy

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I. Motivation and Background

In the case of a vacuum arc thruster (VAT), thrust is provided by the ejection of metal ions ablated from the electrodes. A discharge is ignited between a circular anode and a consumable cathode that constitutes the solid propelling fuel. The VAT considered in this work is manufactured by COMAT. The thruster works in pulsed mode, with repetitive ignition of discharges using high voltage (15 kV). The maximal current reaches 2000 A during a 15 µs pulse. This leads to the formation of a cathode spot causing melting and vaporization of the electrode material, in the present case titanium. The electric field between the electrodes accelerates the charged particles of the plasma that cause the thrust. In order to optimize the thruster performances, it is important to understand the physical phenomena involved in the thrust, as a function of operating parameters. In particular, the charge level of the ejected ions is relevant to estimate the accelerating effect of the electric field and the resulting thrust. According to literature [1], high charge level ions can be observed in such plasma. The emission lines of these ionization levels often fall in far UV wavelength. In addition to ion characteristics, the plasma parameters (electron temperature and electron density) are important for understanding the plume behavior and can be used as input or validation data in modelling. This work presents an optical emission spectroscopic study of the plasma produced by the thruster.

II. Approach

The VAT is placed in a 150 L cylindrical vacuum chamber with a lateral opening containing a set of mirrors (Figure 1). It allows imaging a cross-section of the plasma plume with an optical magnification of 0.55 along a direction “y” perpendicular to thrust axis “z”. Spectra are obtained with an IsoPlane SCT 320 monochromator equipped with an ICCD camera PIMAX4 1024F (both manufactured by Princeton Instrument). While the optics is aligned to observe a fixed position in the plasma, a positioning setup allows moving the VAT along “z” direction in order to choose the measurement target. Apart from position between anode and cathode, referred as “inter electrodes”, it can be set from anode surface (z = 0) up to a few centimeters away in the plasma plume (Figure 1a). In order to observe radiation with wavelength lower than 180 nm (vacuum ultraviolet or VUV) the monochromator is filled with nitrogen gas with a constant flow. Several hours are necessary to get a remaining oxygen level low enough to allow VUV observation. The window of the chamber is made of MgF_2 allowing transmission of VUV (Figure 1b). Acquisition can be integrated over the pulse duration or be triggered with a tunable time delay after pulse start, enabling time resolved analysis over the pulse. Current is measured using a pulse current transformer CT0.5-0.01 (manufactured by Stangenes) with a 15 MHz bandpass. Voltage is measured with a differential voltage probe (manufactured by Elditest) with a 0.001 attenuation factor and a 25 MHz bandpass. Data are recorded using a MSO 44 oscilloscope (manufactured by Tektronix) with a 1 GHz bandpass. The acquisition starts on the basis of a threshold current level and the oscilloscope sends a trigger signal to the ICCD camera to simultaneously start spectra acquisition. Cathode is made of titanium allow including 6%Al, 4%V, and other alloying elements traces.

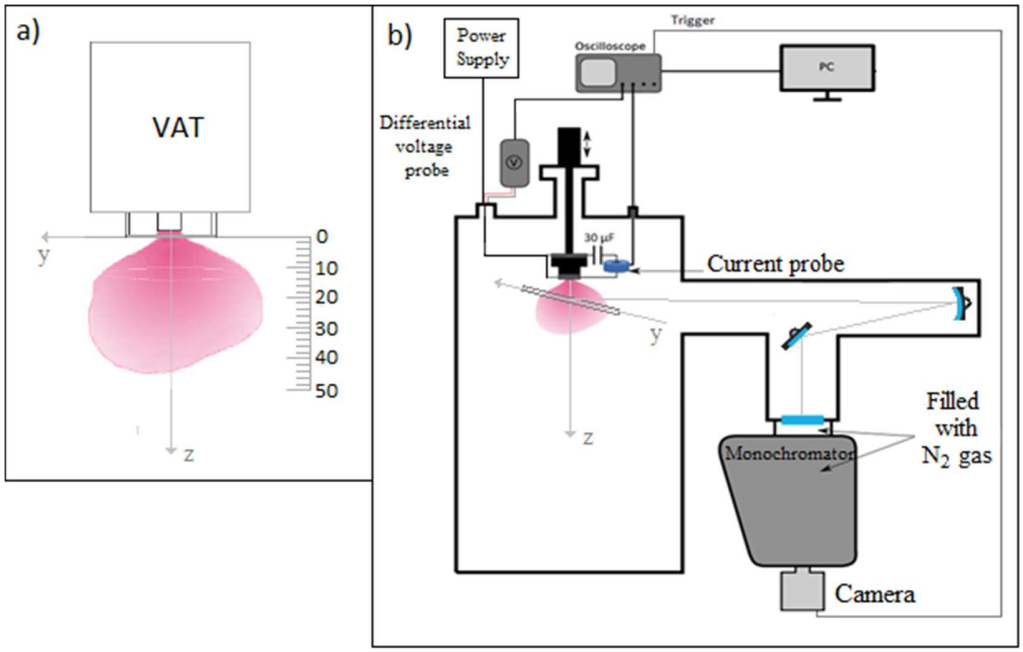

Fig. 1 Experimental setup: a) VAT detail; b) chamber and spectroscopic setup

In a first part, qualitative line detection is performed in order to select usable lines for diagnostic. This also give information on the ionization level of the ejected ions. Plasma temperature is obtained through the Boltzmann plot method, assuming local thermodynamic equilibrium (LTE). Lines are chosen on the basis on good observation conditions (no overlap with other lines, no visible self-absorption) and sufficient departure energy level difference. The relevant spectroscopic data of chosen lines, from NIST database [2], are given in Table 1.

Table 1 Spectroscopic constants of the observed ionized titanium lines Ti+[2].

Wavelength (nm)	As (s^{-1})	E_j (eV)	g_j
326.15845	$1.77.10^8$	5.69194831	12
326.16114	$1.31.10^8$	5.03148088	6
327.89186	$8.83.10^7$	4.86432355	4
328.76542	$1.76.10^8$	5.66282503	10
333.51912	$3.78.10^7$	3.8353753	6
334.03411	$4.27.10^7$	3.82322944	4
334.18741	$1.68.10^8$	4.28283327	8
334.90327	$1.61.10^8$	4.30826569	10
334.94023	$1.68.10^8$	3.74939866	12
337.27927	$1.41.10^8$	3.6866231	8
338.02766	$1.37.10^7$	3.71559942	10
338.375844	$1.39.10^8$	3.66304545	6
338.78334	$2.81.10^7$	3.6866231	8

The precision of the method indeed increases with the difference between emitting levels and should be at least greater than 0.5 eV [3]. In order to avoid reproducibility issues, the used lines are acquired in one single

step, meaning that they can all be observed in the 14 nm wavelength window observable with our setup. On the basis of line detection, 14 singly ionized titanium Ti II lines have been used, with wavelength ranging from 326 to 339 nm. They are well enough isolated in the spectrum for correct line profile measurement and processing [4-6]. The difference between emitting levels reaches 2 eV, ensuring good precision of the method. The electron density is obtained from the Stark broadening of some of these lines (at 328.7 nm, 334.2 nm, and 338.4 nm). Lines were fitted with Voigt profiles considering a Gaussian broadening (Doppler and apparatus function) of 0.03 nm and the Lorentzian part was assumed to correspond to Stark broadening.

Since data are obtained from side-on integrated view, the position on the acquired spectra does not correspond to local values. In order to get information as a function or radial position the Abel inversion [7] is applied assuming plasma plume symmetry along its axis.

III. Preliminary Results

The general spectrum of the plasma shown in Figure 2 is integrated over all the pulse. Two main emission wavelength ranges can be observed, in far UV (below 250 nm) and in the middle of visible range (400-500 nm).

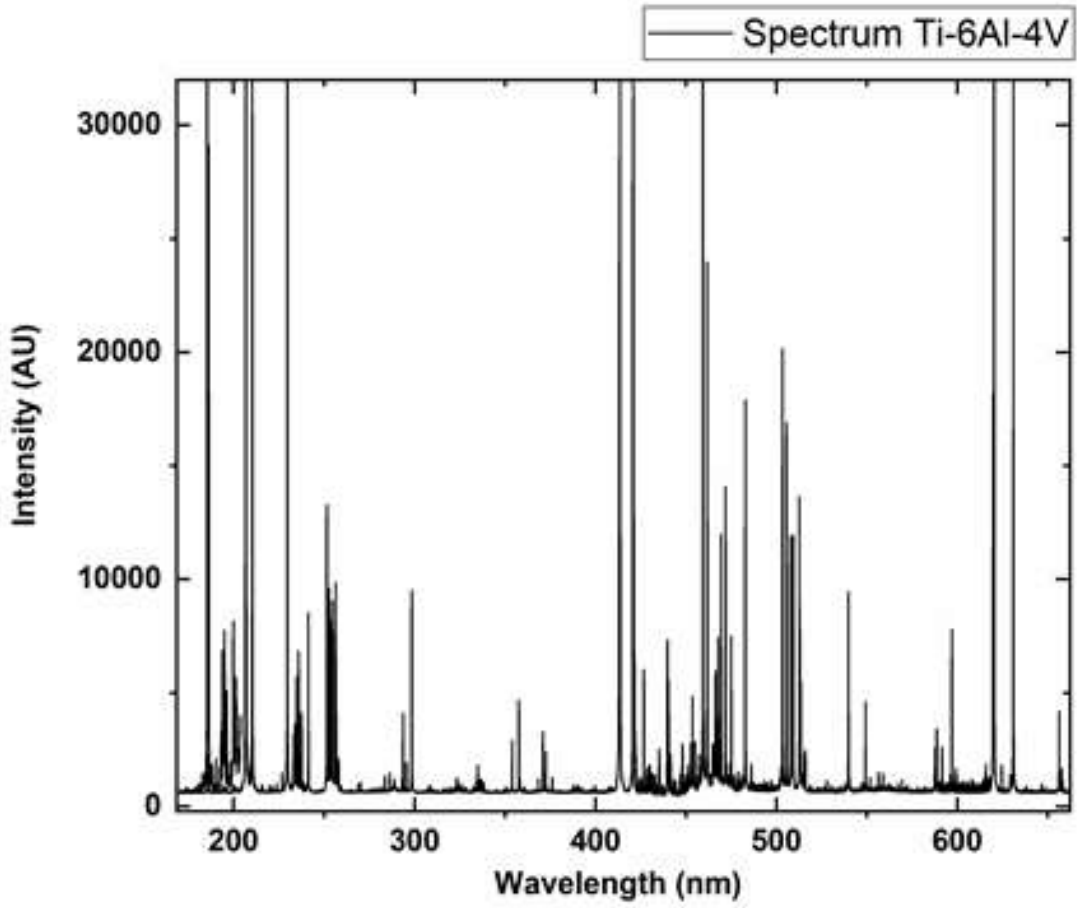

Fig. 2 Global spectrum of plasma plume, inter-electrodes position

Line identification showed the presence of the cathode's components. In addition to titanium (Ti), aluminum (Al), and vanadium (V), elements present as impurities such as iron (Fe) can be detected. Metallic elements generally produced very rich spectra and V or Fe lines with not negligible relative intensity often overlap with titanium lines. Preliminary lines identification seems to indicate ionized level at least up to 4+ (Ti V) in the

lowest observable wavelength range (> 120 nm). While some neutral titanium lines can be observed, the spectrum is dominated with singly ionized titanium lines (Ti II). The relative intensity of the lines used for plasma temperature determination is given in Figure 3. The strongest line corresponds to wavelength of 334.94 nm.

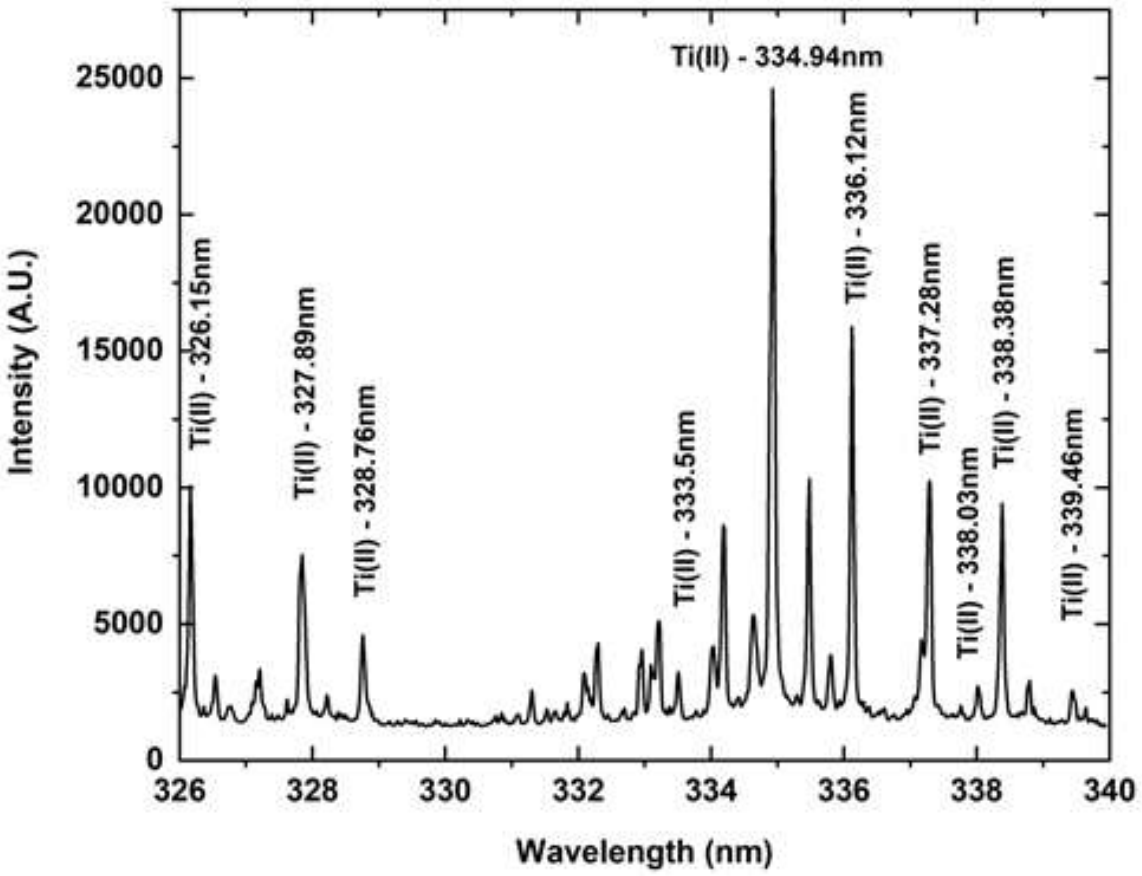

Fig. 3 Relative intensity of the lines used for spectroscopic diagnostic

An example of the Boltzmann plot constructed from of some of these lines is shown in Figure 4. Considering the uncertainties (resulting from both data acquisition and spectroscopic constant uncertainties) the linear fit shows reasonable agreement. The temperature deduced from this fit corresponds to excitation temperature of the considered species, in this case Ti^{+}. On the basis of LTE hypothesis (supported by the relatively good linear fit) one can consider that this represents plasma temperature.

The plasma diagnostic has been made for several positions with respect to anode surface. Temperature radial evolution in inter-electrode position, at 2mm and 7 mm from the anode, is shown in Fig. 5. These result have been obtained by integrating the signal over 35 μs. All profiles exhibit similar behavior, with a maximal temperature observed outside the axis, and a decrease for radial position greater than 4 mm. The highest temperature is observed in inter-electrodes position and reaches 22 000 K. The radial gradient is also stronger at this location. Temperature decreases as one moves away from anode and the gradient reduces: considering the uncertainties one can consider that 7 mm away from anode radial profile becomes flat. The radial limit of 4 mm can be related to the geometry of the anode. It consists in a copper plate pored with a 10 mm diameter hole. As expected, its influence is strong for inter-electrode position and decreases as the plasma plume expands when moving away from electrodes. The lowest temperature is above 14 000 K, which is compatible to the predominance of titanium first level of ionization (Ti II).

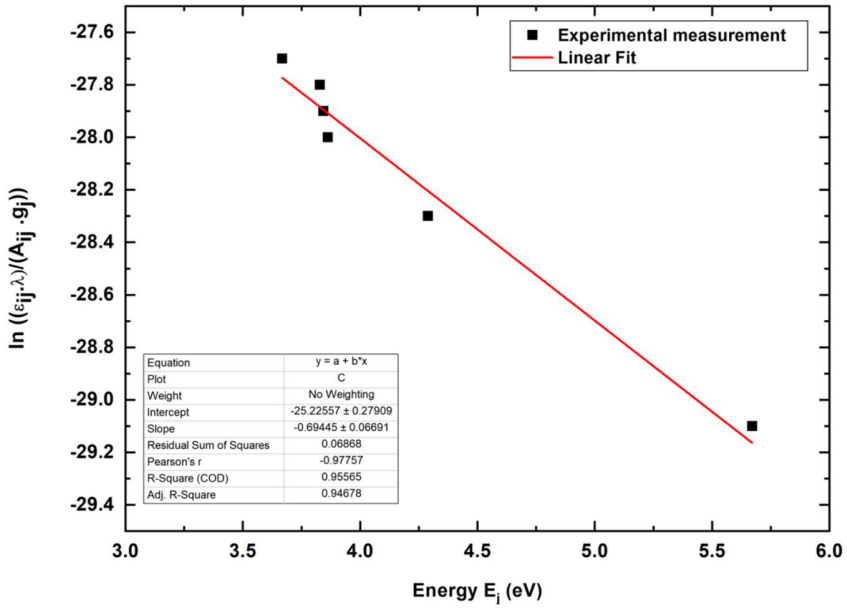

Fig. 4 Example of Boltzmann diagram obtained with some of chosen lines

The lines intensity decrease as one moves away from the anode and for position greater than z = 7 mm it is difficult to get usable signal.

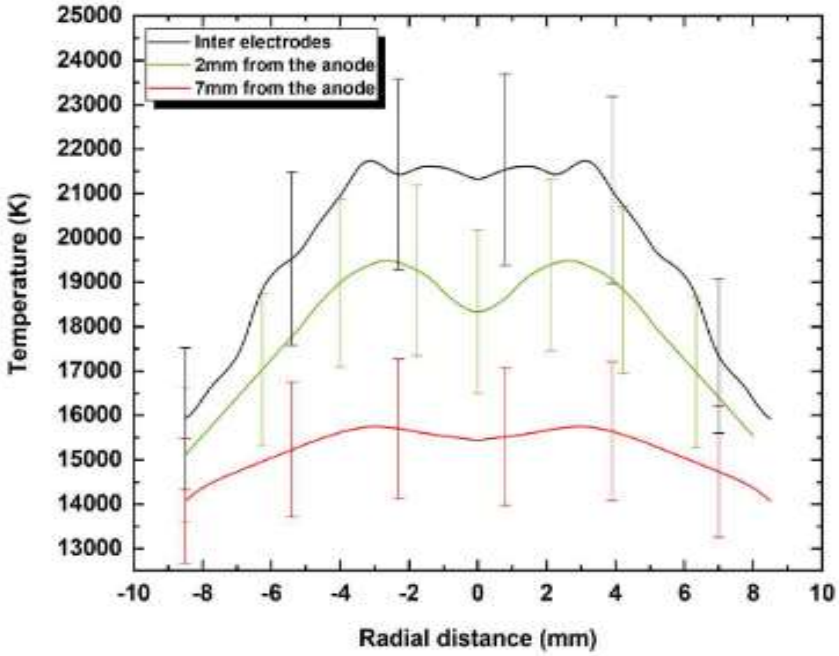

Fig. 5 Temperature radial profile for three positions in the plume

The time evolution of plasma parameters has been obtained by recording data with a time step of 2 μs, starting from the beginning of current pulse and ending 30 μs later. The gating time of the ICCD camera was

2µs. At least three measurements for each case are made in order to check reproducibility. Line intensity is generally weak, in particular during the 12 first µs of the pulse. In order to get strong enough signal, spectra are spatially integrated over all radial position. Results for inter electrode position and 2 mm away from the anode are presented in Figure 6. In order to correlate this evolution with input current, the time evolution of current is plotted in the same graph. It appears that just after arc initiation the temperature is similar for both positions and lies in the range 20 to 25 000 K. Then temperature increases following current rise during the first part of the pulse, with a maximal value greater than 40 000 K. Then 15 µs after pulse start the temperature decreases down to 20 000 K for both positions. However, for the last part of the pulse (20 µs and beyond) temperature does not follow current evolution: as current drops to zero, temperature remains more or less stable. This corresponds to post-discharge mode, with at current extinction still as high as 15 000 K. Maximal peak temperature is higher in the inter-electrodes position but it exhibits lower values in the first rising step.

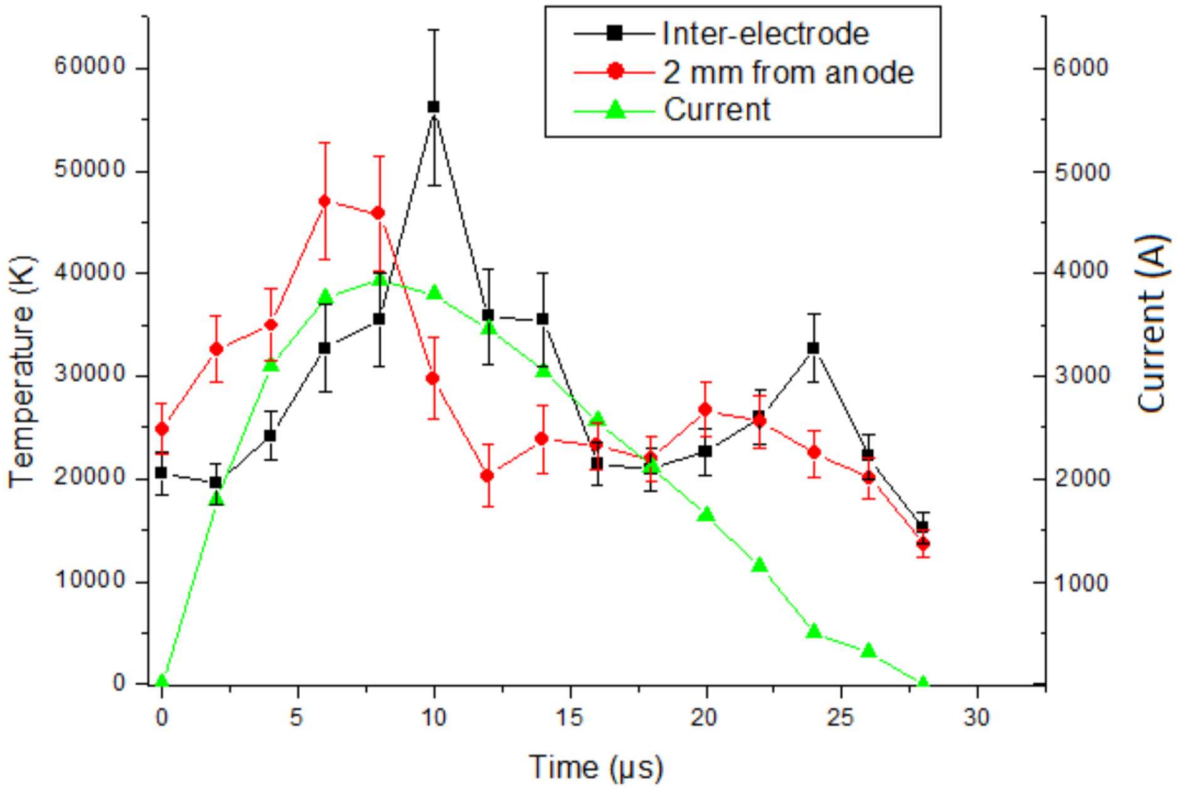

Fig. 6 Time evolution of temperature

According to literature [8], the Stark broadening of lines at 328.7 nm, 334.2 nm, and 338.38 nm is 0.008 nm, 0.0086 nm, and 0.00688 nm of an electron density of $10^{23}m^{-3}$. The obtained density presented in Figure 7 corresponds to the average of these three lines, again for inter-electrode position and 2 mm away from anode.

Electron density reaches $10\times10^{23}/m^3$, which corresponds to pressure greater than atmospheric pressure. On the basis of a LTE calculation a rough estimation yields to the range 300 to 600 kPa in the plasma at the targeted location. Considering that the thruster is operated in vacuum (pressure in the chamber is pumped down to 10^{-5} millibar), such overpressure can be considered as a possible explanation for ion acceleration. Similarly, to the case of temperature, electron density decreases when moving away from anode. Variation over time is higher in the inter-electrode position. One can note however that the densities can be overestimated since the Stark width given in [8] correspond to temperature no higher than 15200 K, which is only the case during the last part of the pulse.

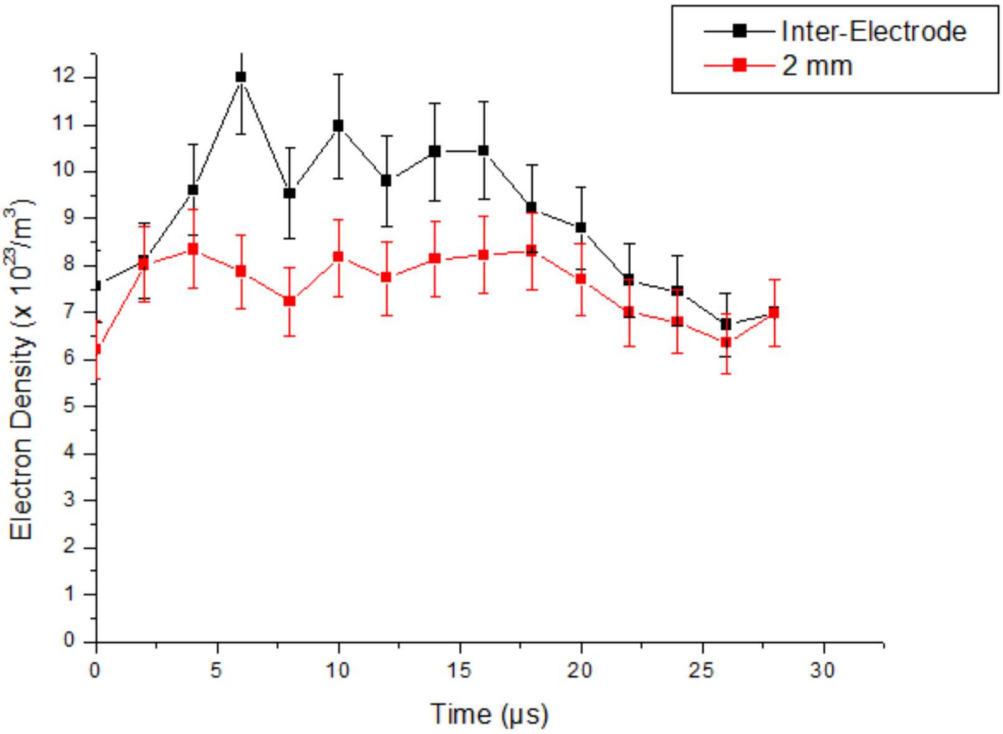

Fig. 7 Time evolution of electron density

IV. Conclusion

The spectroscopic diagnostic confirmed the presence of high ionization level ions. Radial temperature profile close to the anode shows maximum value about 3 mm away from axis on both sides. This can be related to the dimensions of the hole in the anode. The electron density indicates an overpressure during the pulse that confirms that the plasma is actually in the high pressure range (> 100 kPa), despite the low pressure (10^{-3} Pa) operation. This behavior can be related to the phenomena responsible for plasma acceleration and resulting thrust. Further studies will be necessary to confirm the results, in particular by using neutral titanium lines.

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References

[1] G. Yu. Yushkov, A. G. Nikolaev, V.P. Frolova, E.M. Oks, A.G. Rousskikh, and A.S. Zhigalin, "Multiply charged metal ions in high current pulsed vacuum arcs," *Physics of plasma* vol. 24, 2017, pp. 123501_1-7. https://doi.org/10.1063/1.5003676

[2] NIST atomic spectra database: https://physics.nist.gov/PhysRefData/ASD/lines_form.html

[3] F. F. Parada-Becerra, V. Dugar-Zhabon, and P.A. Tsygankov, "Temperature estimation using Boltzmann plot method of titanium emission lines produced on electric arc discharge," *J. Phys.: Conf. Ser.,* Vol. 2046, 2021, p. 012006. 10.1088/1742-6596/2046/1/012006

[4] T. Kratochvil, T. Cernohorsky, P. Knotek, L. Kalina, J. Navesnık, M. Pouzar, and M. Zvolska "Fast determination of the surface density of titanium in ultrathin layers using LIBS spectrometry" *J. Anal. At. Spectrom*, Vol. 29, 2014, p. 1806.

[5] C. M. Figueiredo, J. P. Castro, M. A. Sperança, L. L. Fialho, J. A. Nóbrega, and E. R. Pereira-Filho "Qualitative and Quantitative Chemical Investigation of Orthopedic Alloys by Combining Wet Digestion, Spectroanalytical Methods and Direct Solid Analysis" *J. Braz. Chem. Soc.*, Vol. 29, No. 4, 2018, p. 680-688.

[6] H. Tagreed and S. Hussein "Determination of Species Concentrations of Ti-6Al-4V Titanium Alloys using Calibration Free Laser Induced Breakdown Spectroscopy," *European Journal of Engineering Research and Science,* Vol. 3, No. 50, 2018, 10.24018/ejers.2018.3.8.869.

[7] A. Marotta "Determination of axial thermal plasma 1 temperatures without Abel inversion" *J. Phys. D: Appl. Phys.,* Vol. 27, No. 2, 1994, p. 268.

[8] J. Manrique, J. A. Aguilera, and C. Arag, "Experimental Stark widths and shifts of Ti II spectral lines," *MNRAS*, Vol. 462, 2016, pp. 1501–1507.