doi: 10.56761/EFRE2024.C1-P-027101

# Improving methods for measuring plasma parameters on PBI

*B.Zh. Chektybayev*[1], *M.K. Skakov*[2], *T.R. Tulenbergenov*[1,3], *I.A. Sokolov*[1,3], *A.Zh Miniyazov*[1], *G.K. Zhanbolatova*[1], *R.Zh. Nauryzbayev*[1], *A.V. Gradoboev*[4]

[1] *"Institute of Atomic Energy" Branch of RSE NNC RK, Kurchatov, Kazakhstan*
[2] *RSE "National Nuclear Center of the Republic of Kazakhstan", Kurchatov, Kazakhstan*
[3] *NJSC "Shakarim Semey University", Semey, Kazakhstan*
[4] *National Research Tomsk Polytechnic University, Tomsk, Russia*
**tulenbergenov@nnc.kz*

**Abstract.** As part of the first stage, a system for diagnosing and controlling plasma at Plasma-beam installation (PBI) was created, based on a combination of non-contact and contact measurement methods, with further application at the KTM tokamak. The development of this system will allow obtaining experimental data in the interaction between plasma and materials and will be prerequisites for the development of plasma technologies in the Republic of Kazakhstan. An algorithm and software have been developed for converting and automatically processing the measured current-voltage characteristic (CVC) of the Langmuir probe (LP) and optical emission spectroscopy (OES) into physical values of plasma parameters in real time. A movable input of a cylindrical Langmuir probe located perpendicular to the plasma beam has been developed to measure the radial distribution of plasma parameters. Based on the results of the studies, an evaluation analysis of the plasma characteristics at PBI, obtained by contact and non-contact measurement methods, was conducted.

**Keywords:** PBI, H plasma, plasma diagnostics, Langmuir probe, spectroscopy, plasma parameters.

## 1. Introduction

A linear PBI has been created in National Nuclear center of the Republic of Kazakhstan to support of the KTM tokamak operation [1]. The PBI is an experimental platform for the preliminary testing of the diagnostic equipment, conducting small-scale experimental work in the field of the plasma-surface interaction.

The similar imitation installations can realize close temperatures and the plasma density with the scrape off the layer (SOL) [2–5].

When the plasma interacts with the surface, such processes as spraying or erosion of the chamber material surface, spraying and embedding foreign particles into the surface, modification of the relief and blister formation on the surface occur [6, 7]. Moreover, in the plasma beam discharge (BPD) there are processes such as ionization and recombination of the atoms and molecules, excitation and radiation of the atoms and molecules in the visible and ultraviolet ranges, non-stationary and inhomogeneous state caused by the effects of instability, wave phenomena, turbulence, etc.

At present, there are many ways which are based on non-contact and contact methods of the plasma diagnostics to measure various plasma parameters. Despite the fact that the probing element perturbs the plasma, the contact methods allow characterizing the plasma parameters the best way. The most famous contact method is the Langmuir probe, as it is suitable for the local determination of the density, temperature of the charged plasma particles and space potential. To date, the Langmuir probe is widely used in tokamaks to determine the plasma parameters in the divertor area [8, 9].

The OES, based on the analysis of the intensity and shape of the spectral lines of atoms and ions in a plasma, provides valuable information about the state of a plasma object without directly influencing it, which makes it especially valuable for studying plasma characteristics [10, 11].

Currently, work is being carried out at PBI to study the interaction of various types of plasma with beryllium, the processes of formation of carbides in tungsten and interaction with helium plasma, modification and erosion of the surface of tungsten and molybdenum under the influence of low-temperature plasma, as well as the processes of formation of "fuzz" on the surface of tungsten [12, 13]. When studying the kinetics of processes occurring in chemically active plasma, which is used when interacting with materials, information about the parameters of the electronic component of the plasma is of great importance, so there is a need to determine the parameters of the exposure to radiation.

In general, automation of plasma diagnostic methods makes it possible to increase the efficiency, accuracy and repeatability of results when conducting research, as well as to understand in detail the processes occurring in plasma. Despite the widespread use and development of the methods the PBI has its own characteristics and requires the adaptation and refinement of the selected plasma diagnostic system.

When studying such processes, it becomes necessary to determine the parameters of the exposure. Based on the above, the purpose of this work is to measure plasma parameters in PBI using an automated system developed by us based on contact and non-contact plasma diagnostics.

## 2. Research methods and equipment

### *2.1 Plasma-beam installation*

Development of an automated system for contact and non-contact plasma diagnostics and measurements were carried out at PBI. The installation uses collision less interaction of an electron beam with gas to create low-temperature plasma for testing materials under various conditions. It is compact and includes an electron beam gun, vacuum chambers, and diagnostic systems. The plasma produced has high ion energy and particle flux, and diagnostic methods like pyrometry and mass spectrometry are used to monitor it. Various gases can be used as the working gas.

### *2.2 Development of an algorithm for processing the experimental CVC*

An algorithm and software have been developed for recalculation and automatic processing of the measured CVC of an electric probe into the physical values of the plasma parameters in real time. The methodology for determining the plasma parameters using the probe diagnostics has been worked out for the software, which includes an algorithm for measuring, recording, and processing the experimental data in order to determine the local plasma parameters.

Two approaches are used for processing the current-voltage curve data, involving different sections of the curve. The data is processed to eliminate noise and calculate plasma potential, electron temperature, and plasma concentration. The algorithm involves various mathematical calculations and graphical analyses to determine these parameters accurately.

### *2.3 Determination of plasma density using optical spectrometry*

A technique has been developed for determining the plasma density using optical emission spectrometry based on the broadening of spectral lines due to the interaction of charged particles (electrons and ions) with atoms or molecules in the plasma. Thus, the determination of the ion density is directly related to the measurement of the electron concentration ne in the plasma beam discharge.

Density estimation using low-temperature plasma optical emission spectrometry can be accomplished by several spectral methods. One of the most commonly used methods is based on measuring the broadening of spectral lines resulting from the Stark effect [14, 15]. The Stark effect in low-temperature plasma is associated with the broadening of spectral lines due to the interaction of charged particles (such as electrons and ions) with atoms or molecules in the plasma. The degree of broadening depends on the electric field strength and the number of charged particles in the plasma. In this regard, the Stark effect is widely used as a diagnostic tool at PBI to determine the density of charged particles in plasma.

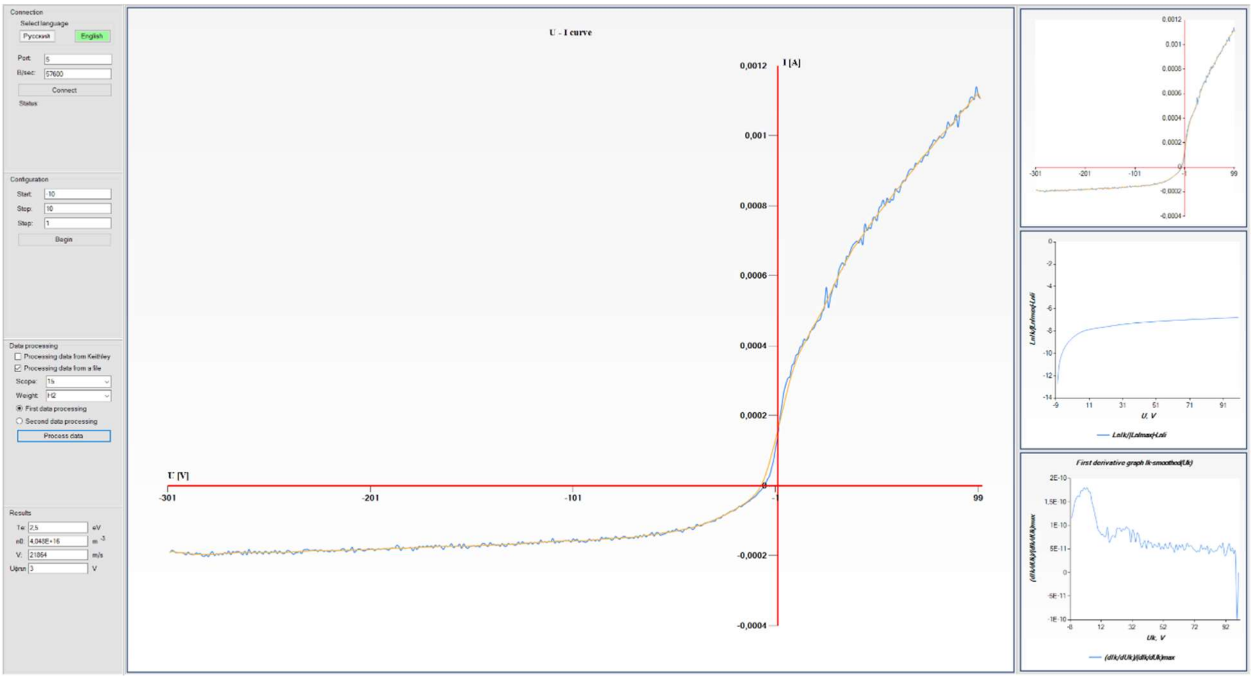
### *2.4 Development of an automated diagnostics system at the PBI*

When creating the automated system for probe diagnostics of the plasma parameters at PBI, the problems of developing a movable cylindrical Langmuir probe, integrating a special scanner and working out the software for the automatic CVC processing and the output of the plasma parameters in real time were solved. To record the current and voltage on the probe, an analog-to-digital converter with grounded channels is used. For the measurement, a tungsten electrode with a collecting surface area of 4.91 mm$^2$ was used, it had a length of 3 mm and a diameter of 0.5 mm, the insulating part of the probe was made of BeO.

The operating principle of the automated probe diagnostic system is as follows: when the cylinder with process nitrogen is opened, the pneumatic distributor is in the neutral position when all supply and pressure relief paths are closed. The position of the probe electrode is as far as possible from the beam axis. When specifying the required point for measuring the CVC, the program sends a signal to the pneumatic distributor, which opens the nitrogen supply path to move the rod in the pneumatic cylinder. When the probe electrode reaches a specified position, the program automatically stops sending a signal to the pneumatic distributor and simultaneously sends a signal to start the scanning unit. In this case, the position of the probe electrode remains fixed. After completion of the scanner operation, the obtained current and voltage values are transferred to the program for subsequent processing.

The spectroscopic measurements at the PBI are carried out using two optical spectrometers manufactured by Avantes. The single-channel fiber-optic spectrometer of the Avaspec-2048 model is used for the absolute measurements. If high optical resolution is required, an Avaspec-4096-4 fiber-optic spectrometer with four independent measurement channels is used.

As part of the integration of the algorithm into the PBI IMS, the C# programming language and the Microsoft Visual Studio integrated development environment were used, along with several other tools. These tools include a source code editor with support for IntelliSense technology and the ability to perform simple code refactoring. C# is a part of the .NET platform, which grants extensive access to libraries that streamline software development and creation. The software development includes modules for data collection, processing, visualization, control, and stable operation to analyze plasma parameters in real-time. As a result, software was developed, which is shown in Fig. 1a and 1b.



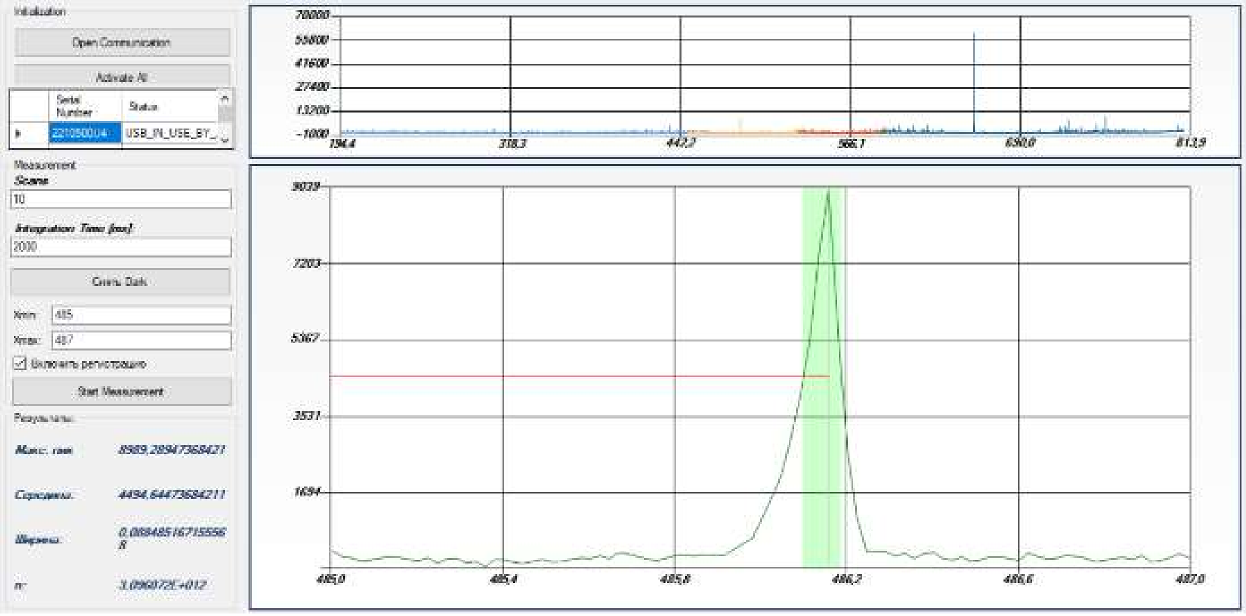
Port: 5
B/sec: 57600

Start: -10
Stop: 10
Step: 1

☐ Processing data from Keithley
☑ Processing data from a file
Scope: 15
Weight: H2
● First data processing
○ Second data processing

Te: 2,5 eV
n0: 4,048E+16 m$^{-3}$
V: 21864 m/s
Uprn 3 V

Fig. 1a. General view of the program for processing CVC.



221050004 USB_IN_USE_BY_

Scans: 10

Integration Time [ms]: 2000

Xmin: 485

Xmax: 487

☑ Включить регистрацию

Макс. сим: 8989,28947368421

Середина: 4494,64473684211

Ширина: 0,08848516715556 8

n: 3,096072E+012

Fig. 1b. Optical spectra.

## 3. Results and discussions

The arithmetic mean values of the electron temperature ($T_e$) and the plasma concentration ($n_e$) depending on the accelerating voltage of the electron beam in a hydrogen medium at a working gas pressure in the interaction chamber of $1 \cdot 10^{-3}$ Torr were obtained during the experimental work using an automated system. As a result of the obtained experimental data, the graphs of the plasma parameters in the radial direction have been constructed, they are shown in Fig. 2.

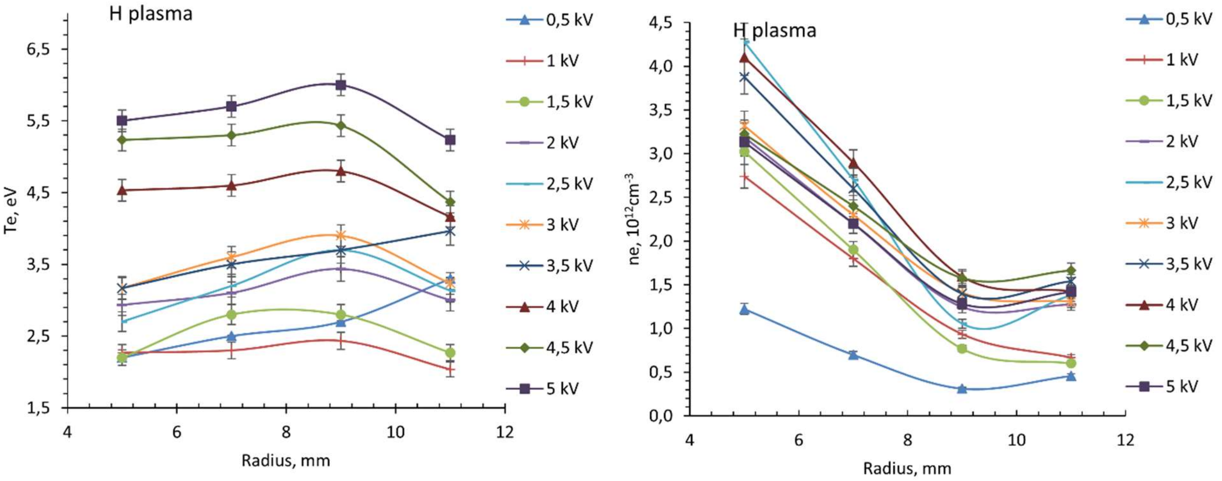


Fig. 2. Dependence of the electron temperature ($T_e$) on the left and the plasma concentration ($n_e$) on the right upon the accelerating voltage of an electron beam in a hydrogen medium at a working gas pressure of $1 \cdot 10^{-3}$ Torr.

The graphs show that with an increase in the accelerating voltage from 0.5 kV to 5 kV, the electron temperature ($T_e$) increased from ~2.2 eV to ~5.7 eV and is uniform in the radial direction. The plasma concentration ($n_e$), reached the saturation to a value of ~ $4.3 \cdot 10^{12}$ $\text{cm}^{-3}$ when achieving an accelerating voltage of up to 2.5 kV, and decreases in the radial direction. The graphs of the dependence of the electron temperature ($T_e$) and plasma concentration ($n_e$) on the hydrogen pressure at an accelerating voltage of 2.5 kV in the radial direction have also been constructed, they are shown in Fig. 3.

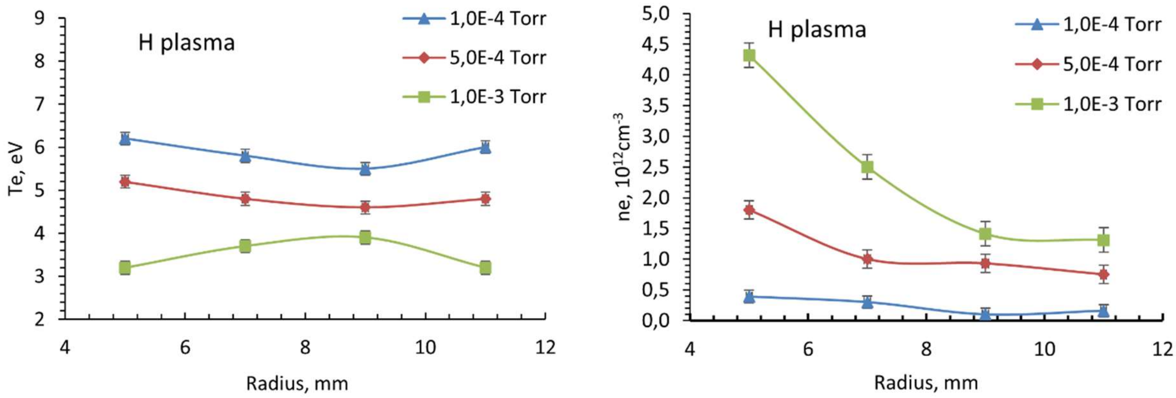


Fig. 3. Dependence of the electron temperature ($T_e$) (on the left) and the plasma concentration ($n_e$) (on the right) on the hydrogen pressure at an accelerating voltage of 2.5 kV.

The graphs show that with an increase in the pressure of the working gas from $1.0 \cdot 10^{-4}$ Torr to $1.0 \cdot 10^{-3}$ Torr, the electron temperature in the radial direction is uniform and increases from ~3.2 eV to ~6.2 eV at a pressure of $1.0 \cdot 10^{-4}$ Torr. The plasma concentration increases with the pressure increasing and decreases radially, and it is uniform at a distance from 9 mm to 11 mm. The maximum plasma concentration was $\sim 4.3 \cdot 10^{12}$ cm$^{-3}$ at a distance of 5 mm. The measurement of the radial distribution by a single probe at a distance of less than 5 mm was limited to the area of the primary electron beam, where the probe was overheated as a result of thermal emission from its surface.

## 4. Conclusion

The experimental work has been carried out at the PBI to determine the plasma parameters in the periphery using an automated system for diagnostics and control of the plasma in the hydrogen environment developed by us. The measurements were carried out under different operating modes of the PBI with a variation in the parameters of the electron beam accelerating voltage and the working gas pressure. The nature of changes in electron temperature ($T_e$) and plasma concentration ($n_e$) has been established. The regularity of the results is in good agreement with similar work in the study of the plasma parameters in the radial direction on the linear plasma installations.

A spectroscopic system consisting of two optical spectrometers was used to study the emission spectrum of PBI plasma in the wavelength range of 200–800 nm. The main lines of working gas and plasma impurities were identified for the first time. The discovered spectral lines indicate the presence of small amounts of impurities in the plasma, such as oxygen (O), nitrogen (N), molybdenum (Mo), and tungsten (W). Spectroscopic analysis in various operating modes of the plasma source revealed changes in the plasma spectrum depending on changing experimental conditions. Clear changes in the emission spectrum were observed when varying the accelerating voltage and pressure.

An algorithm has been developed for calculating automatically the measured CVC of the probe into the physical values of the plasma main characteristics and the software for the real-time data output on the basis of the literature analysis. The algorithm is based on well-known and proven methods using standard mathematical functions and analytical interpretation of graphical methods. The presented engineering idea will be proposed to complement the diagnostic complex of the KTM tokamak plasma.

Thus, the obtained dependences will allow analyzing and establishing a correspondence between the parameters of the plasma exposure to the materials and the nature of processes on their surface, as well as in volume, and studying the dynamics of the development of these processes from the irradiation duration, the discharge types and parameters. At present, the work is underway to supplement the developed contact diagnostic system with the optical plasma diagnostics with the ability to estimate the plasma density in the BPD central part also in real time.

**Acknowledgement**

This work was carried out within the framework of grant funding by the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP13068552).

## 5. References

[1] A.A. Kolodeshnikov, V.A. Zuev, D.A. Ganovichev, et al., Simulation stand with a plasma beam installation, *patent of the Republic of Kazakhstan No. 2080 applicant and patent holder RSE NNC RK.*– No. 2016/0108.2; application 02/29/2016; publ. 03/15/2017, Bulletin. No. 5. p.3.

[2] X. Yue, et al., Plasma-surface interaction experimental device: PSIEC and its first plasma exposure experiments on bulk tungsten and coatings, *Fusion Engineering and Design*, vol. **164**, no. 112198, 2021; doi: 10.1016/j.fusengdes.2020.112198

[3] M.J. Baldwin, et al., Plasma-Material-Interaction Research Using PISCES Linear Plasma Devices, *Fusion Science and Technology*, vol. **75**, Issue 7, 2019; doi: 10.1080/15361055.2019.1646608

[4] N. Ohno, et al., Investigation of recombination front region in detached plasmas in a linear divertor plasma simulator, *Nuclear Materials and Energy*, vol. **19**, 458, 2019; doi: 10.1016/j.nme.2019.03.010

[5] H.J.N. van Eck, et.al. High-fluence and high-flux performance characteristics of the superconducting Magnum-PSI linear plasma facility, *Fusion Engineering and Design*, vol. **142**, 26, 2019; doi: 10.1016/j.fusengdes.2019.04.020

[6] M. Skakov, G. Zhanbolatova, A. Miniyazov, et al., Impact of High-Power Heat Load and W Surface Carbidization on its Structural-Phase Composition and Properties, *Fusion Science and Technology*, vol. **77**(1), 2021; doi: 10.1080/15361055.2020.1843885

[7] M. Skakov, A. Miniyazov, E. Batyrbekov, et al., Influence of the Carbidized Tungsten Surface on the Processes of Interaction with Helium Plasma, *Materials*, vol. **15**, 2022; doi: 10.3390/ma15217821

[8] Y. Wang, et al., Design of electronics system for Langmuir probes on ITER, *Fusion Engineering and Design*, vol. **152,** № 111429, 2020; doi: 10.1016/j.fusengdes.2019.111429

[9] S.C. Liu, et al., Development and application of limiter Langmuir probe array in EAST, *Fusion Engineering and Design*, vol. **180**, no. 113162, 2022; doi: 10.1016/j.fusengdes.2022.113162

[10] W. Olchawa, R. Olchawa, and B. Grabowski, Stark broadening of hydrogen spectral lines with fine structure effects, *Journal Eur. Phys*, vol. **28**, 119, 2004; doi: 10.1140/epjd/e2003-00291-5

[11] J.M. Palomares Linares, S. Hubner, E.A.D. Carbone, N. de Vries, E.M. van Veldhuizen, A. Sola, A. Gamero, and J.J.A.M. van der Mullen, H β Stark broadening in cold plasmas with low electron densities calibrated with Thomson scattering, *Spectrochimica Acta. Part B: Atomic Spectroscopy*, vol. **73**, 39, 2012; doi: 10.1016/j.sab.2012.07.005

[12] M.K. Skakov, et al., Changes in structure of the surface and edges of beryllium plates as a result of thermal cycling tests, *Fusion Engineering and Design*, vol. **183**, no. 113251, 2022; doi: 10.1016/j.fusengdes.2022.113251

[13] T.R. Tulenbergenov, et al., Formation of "Fuzz" on the Pre-Nitrided Tungsten Surface, *Physics of Atomic Nuclei*, vol. **82**, 1454, 2019; doi: 10.1134/S1063778819120299

[14] N. Zhang, F. Sun, L. Zhu, M.P. Planche, H. Liao, C. Dong, and C. Coddet, Electron Temperature and Density of the Plasma Measured by Optical Emission Spectroscopy in VLPPS Conditions, *Journal of Thermal Spray Technology*, vol. **20**(6), 2011; doi: 10.1007/s11666-011-9681-6

[15] D.M. Devia, L.V. Rodriguez-Restrepo, and E. Restrepo-Parra, Methods Employed in Optical Emission Spectroscopy Analysis: a Review, *Ingeniería y Ciencia*, vol. **11**(21), 239, 2015; doi: 10.17230/ingciencia.11.21.12