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GENERATION AND ACCELERATION OF STEADY-STATE PLASMA IN PLM-M DEVICE FOR TESTING OF FUSION MATERIALS

S.D. FEDOROVICH
National Research University "MPEI"
Moscow, Russian Federation
Email: fedorovichsd@mail.ru

A.V. DEDOV
National Research University "MPEI"
Moscow, Russian Federation

V.P. BUDAEV
National Research University "MPEI"
Moscow, Russian Federation

D.I. KAVYRSHIN
National Research University "MPEI"
Moscow, Russian Federation

M.V. LUKASHEVSKY
National Research University "MPEI"
Moscow, Russian Federation

D.V. PEREGUDOV
National Research University "MPEI"
Moscow, Russian Federation

M.K. GUBKIN
National Research University "MPEI"
Moscow, Russian Federation

Q.V. TRAN
National Research University "MPEI"
Moscow, Russian Federation

K.A. ROGOZIN
National Research University "MPEI"
Moscow, Russian Federation

Abstract

Tests of plasma-facing in-vessel materials in modern tokamaks and experimental testing of in-vessel components of the ITER tokamak-reactor have revealed a number of significant problems related to the durability of structural materials under plasma, beam, and thermal loads expected in a fusion reactor [1]. Testing of materials and mock-ups under high steady-state loads up to 10 MW/m^2 in plasma devices is necessary to predict their performance in a reactor [2]. This requires the development and creation of steady-state plasma devices with methods for additional plasma heating and acceleration. The PLM-M plasma device created at the National Research University "MPEI" is used for testing the thermal protection cladding of in-vessel components of a fusion reactor with steady-state plasma flows having parameters similar to the tokamak edge and divertor plasma. This report presents the results of a study on the generation and acceleration of steady-state plasma flows in the PLM-M device for application in fusion materials testing.

1. INTRODUCTION

The expected plasma-thermal loads on divertor plates (based on calculations for ITER [2,7]) in an ITER-scale tokamak during the steady-state DT discharge phase will reach ~10–15 MW·m^{-2}, leading to an average surface temperature increase of the material to ~1100 °C. The plasma-thermal load on the first wall will be over 1 MW/m². During disruptions and ELMs, short-term impulsive loads on divertor plates will reach gigawatt-scale magnitudes of 0.6–3.5 GW·m^{-2} [8], which will cause periodic increases in the material temperature to values close to the melting point of tungsten. Such powerful loads can lead to surface overheating, crack formation, and even melting of tungsten [5]. Therefore, it is necessary to assess the consequences of possible tungsten melting and cracking, recrystallization, formation of heterogeneous and porous layers on the surface of tungsten plates under critical and subcritical thermal loads, and the formation of dust particles after the destruction of such layers. Studies of tungsten durability under powerful plasma-thermal loads have been conducted in experiments on tokamaks JET, AUG, T-10, Alcator C-Mod, the LHD stellarator, linear plasma devices, pulsed plasma accelerators like QSPA-T, in electron- and ion-beam devices, and in laser experiments [1]. It should be noted that some important processes that could lead to the destruction of tungsten divertor plates in a fusion reactor (ITER, FNS, and DEMO) have not been investigated in experiments. For this reason, additional research is required, aimed at developing elements of the cooled thermal protection cladding for the chamber of the developing fusion neutron source FNS and fusion reactors ITER and DEMO. Research in previous years [5, 9, 10] has shown the promise of using linear devices with magnetized plasma – divertor simulators – for testing in-vessel reactor components. For these purposes, the PLM-M device [3] was costructed at the National Research University "MPEI" based on the device [6]. In 2023-2025, a significant modernization of this device was carried out using the RF plasma generation for testing fusion materials.

2. RESEARCH METHODS

The PLM-M device [3] is a linear magnetic trap with a multi-cusp magnetic plasma confinement scheme. The design schematic of the device is shown in Fig. 1. The magnetic system of PLM-M consists of two solenoids and an eight-pole multi-cusp system. The magnetic field reaches 0.035 T in the center of the cylindrical plasma discharge *4* and up to 0.2 T in the cusps at the periphery of the discharge chamber. In the main volume of magnetic confinement, the hot zone of the cylindrical plasma discharge has a diameter of 3.5 cm. Two plasma sources are used with the possibility of their combination: a beam source with ionization of atoms by electrons accelerated by a constant electric field between the cathode and anode, and a helicon source with ionization of atoms and RF plasma heating by the RF field of a cooled helicon antenna isolated from the plasma by a quartz tube. Water cooling is used to ensure steady-state operation of the helicon antenna, the device's discharge chamber, and other systems. The layout of the main systems of the PLM-M device is shown in Fig. 2. The developed matching device (Fig. 2) allows transferring up to 95% of the RF generator power to the plasma.

A feature of the PLM-M device is the steady-state mode of multi-hour plasma confinement, which is an advantage for testing fusion reactor materials, studying the physics of turbulent plasma, and developing plasma technologies. The powerful plasma flow in PLM-M is used for testing materials and in-vessel components of the fusion reactor, as well as for irradiating materials to modify them and achieve new physical and chemical properties. Research on the generation and acceleration of steady-state plasma flows for application in fusion materials testing is being conducted on the PLM-M device [3]. The plasma-thermal flux on the plasma-facing surface of the test sample was determined from measured values of the ion saturation current and electron temperature according to the method described in [16]. The parameters of the steady-state plasma flow of the PLM-M device were measured by Langmuir probes and optical diagnostics [17].

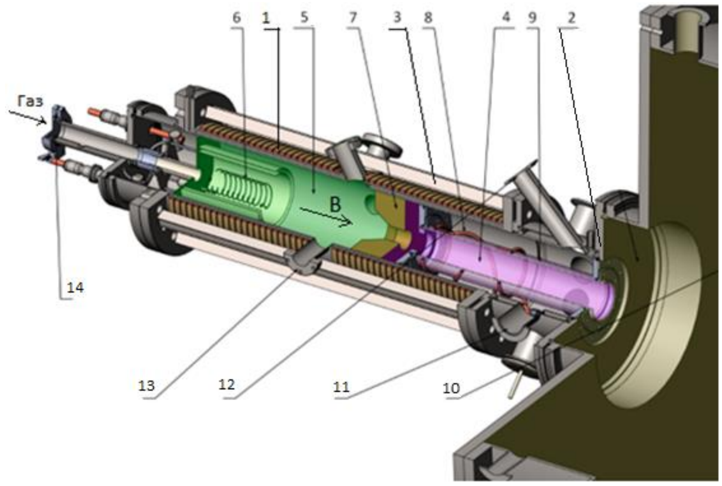

FIG. 1. 3D schematic of the PLM-M plasma device: 1,2 – solenoids; 3 - eight-pole multi-cusp system; 4 - center of the cylindrical plasma discharge; 5 - cusp zone at the periphery of the discharge chamber; 6 -- cathode; 7 - anode; 8 - cooled helicon antenna; 9- quartz tube; 10 - receiver; 11,12,13 -- diagnostic windows; 14 - current feedthrough.

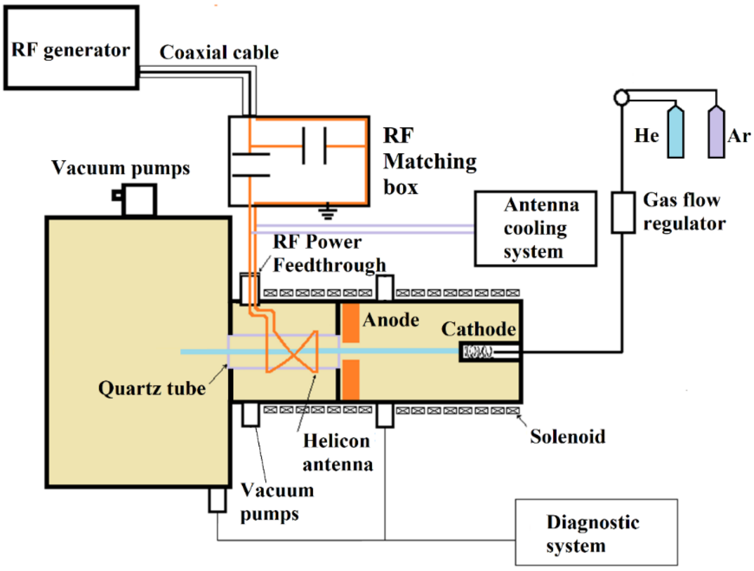

FIG. 2. The systems of the PLM-M device

The velocity of the ion flow (Ar+) was determined experimentally using the Gundestrup probe method [4]. Probes made of tungsten wire were placed inside four longitudinal channels of a cylindrical ceramic insulator. The probe diameter was 0.8 mm. The dimensions of the longitudinal cuts in the insulator were 6 mm in length and 1 mm in width. The probes were inserted into the plasma using a manipulator in the region where the plasma flow exits the helicon antenna.

3. RESEARCH RESULTS

The electron temperature was measured using a spectral method based on the intensity ratios of the most intense lines in the ultraviolet, visible, and near-infrared wavelength ranges: the He II line at 468.5 nm and the He I line at 471.3 nm with known electron excitation functions. With additional RF plasma heating using the helicon antenna - electron density $\sim 10^{19}$ m^{-3}, electron temperature ~10 eV, parameters depended on the plasma current (Figs. 3, 4). Measurements using probe diagnostics allowed determining the plasma parameters in the discharge during tests depending on the discharge modes: electron temperature from 1 eV to 10 eV, electron density from $0.5 \cdot 10^{19}$ m^{-3} to $3 \cdot 10^{19}$ m^{-3}. Such powerful plasma flows can be used for testing materials and structures of in-vessel fusion reactor components [11-13], developing plasma technologies [18] and electro-reactive thruster technology for space applications [14], and testing modern heat transfer enhancement methods [15].

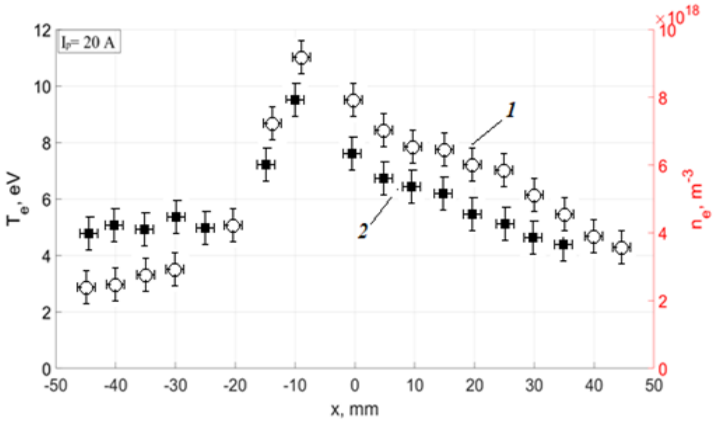

FIG. 3. Plasma parameters in PLM-M: (1) radial distribution of electron temperature T_e and (2) - electron density n_e, plasma current of 20 A. RF heating power 950 W

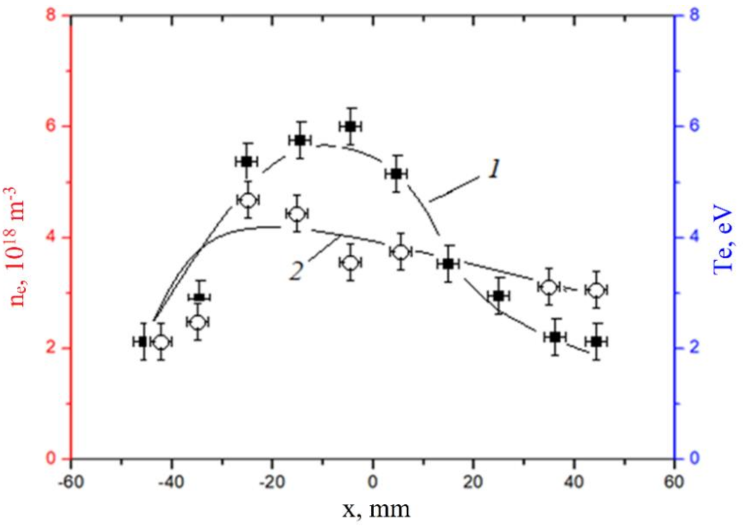

FIG. 4. Plasma parameters in PLM-M: radial distribution of (1) - electron density n_e, plasma current 8 A and (2) - electron temperature T_e

To measure the erosion of the plasma-facing surface, plasma tests of a tungsten mock-ups with a cooling system were conducted in the PLM-M device [3]. Cooling was performed by a dispersed water-air flow. Water pressure in the cooling system flow was 3.6 atm, air pressure 8 atm, water flow rate 1 *l*/min, air flow rate 45 *l*/min. The plasma discharge current during module testing was 6.1 A, plasma irradiation duration 120 min. In this test mode, the load on the module surface was more than 1 MW/m², estimated based on the calculation of the heat flux to the surface using measured near-surface plasma parameters and tungsten temperature values measured by thermocouples [16]. To apply additional load to the tungsten during plasma tests in PLM-M, a neodymium laser was used, simulating the ELMs. After plasma tests of the tungsten mock-ups in the PLM-M device, no large-scale destruction or melting of the module was observed, Fig. 5. No significant macroscopic changes of the tungsten surface (initially smooth), large-scale cracks or spalling on the surface, or significant erosion of the tungsten mock-ups were observed after two hours of plasma testing in PLM-M. The possibility of modeling arc discharge conditions above the tungsten surface using laser radiation in the upgraded PLM-M device was experimentally confirmed. Studies of the combined effect of steady-state plasma and powerful impulsive laser loading on the material were conducted. Studies of the effects of laser loading and powerful electron-beam loading on a highly porous surface were carried out. The surface "fuzz" layers on tungsten samples degrade insignificantly under powerful laser and electron-beam loads. To obtain dense near-surface tungsten plasma for arc ignition near the sample surface, a pulsed Nd:YAG laser with a wavelength of 1064 nm, pulse duration of 10 ns, and pulse energy of 0.5 J was used. The power density of the laser pulse impact on the sample surface was 2.1×10^{13} W/m², considering the area of the elliptical spot.

a) b)

FIG. 5. Tungsten mock-up during plasma tests in PLM-M (a) and its surface after tests in PLM-M (b)

4. CONCLUSION

In the PLM-M plasma device – a divertor simulator, plasma is generated for testing the thermal protection cladding of in-vessel fusion reactor components with steady-state plasma flows having parameters similar to tokamak edge and divertor plasma. A feature of the PLM-M device is the steady-state mode of multi-hour operation with magnetized plasma with high plasma parameters. With additional RF plasma heating using the helicon antenna - electron concentration ~10^{19} m^{-3}, electron temperature ~10 eV. A significant influence of the direction of the longitudinal component of the magnetic field on the acceleration of the plasma flow by the helicon antenna was experimentally discovered. The conducted analysis of the surface after plasma tests did not reveal macroscopic changes (significant erosion, large-scale cracks, or spalling) of the tungsten mock-up surface after plasma tests in PLM-M; traces of arcing processes were detected on the plasma-facing tungsten surface. Based on the test results of the tungsten mock-up in PLM-M and considering the expected loads on the tungsten plates of the ITER divertor, the operating mode of the mock-up's cooling system was selected for performing plasma tests in PLM-M with steady-state loads on the material from 1 to 5 MW/m^2. Tests of cooled tungsten mock-ups of in-vessel component cladding are planned in PLM-M to assess their erosion in ITER and to develop designs for the thermal protection cladding of the TIN chamber.

ACKNOWLEDGEMENTS

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