The plasma device for the high-heat plasma testing of refractory metals and inventing of new highly porous materials

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Abstract. A unique plasma device has been constructed at the NRU "MPEI" for the study of plasma-surface interaction and the high-heat plasma testing of refractory metals, such as tungsten, molybdenum, steel and other plasma facing materials used in fusion reactor including the ITER. This plasma device is a multi-cusp linear stationary plasma confinement system. It has power-saving characteristics as well as compactness due to the employment of the 8-pole multicusp magnetic field configuration instead of a strong axial magnetic field. Experiments are planned to develop a novel technology for highly porous surface structure of the refractory metal with a pore size and nanofibers of 50 nanometers including tungsten “fuzz”.

1. Introduction

Plasma-wall interaction (PWI) in a fusion device leads to the change of the material surface morphology influenced by several mechanisms including erosion, melting and melt motion over the surface, redeposition of eroded materials, solidification and recrystallization (see [1,2]). Recently, stochastic surface clustering with hierarchical granularity and statistical self-similarity (fractality) were detected on materials under plasma high heat load. E.g., in experiments with helium plasma in high-temperature plasma facilities, a surface with a pore size and nanofibers up to 50 nanometers and high roughness is formed on refractory metal. Such nanostructured metals are needed to use in plasma/beam devices [1] including fusion reactors, for coating streamlined surfaces of aircrafts to reduce the aerodynamic drag at supersonic and hypersonic speeds, for synthesis of new nanostructured materials with programmed properties and organometallic composite materials in biotechnology and biomedical applications, as a matrix for the growth of the organometallic complex compounds. Nanostructured metals and their oxides are materials for use as active layers in gas microsensors, as catalysts in hydrogen technologies. For the realization of the ITER (International Thermonuclear Experimental Reactor), as well DEMO (DEMonstration Reactor) and FNS (Fusion Neutron Source), material selection for the plasma-facing components inside the reactor is essential to ensure stable sustainment of tokamak plasma confinement. Tungsten is one of the most promising candidates owing to its high melting temperature and low sputtering yield. However, we do not have sufficient characterization of tungsten as the plasma-facing material. For example, the formation of nanostructure morphologies and a damaged surface may have weak thermal resistance due to lost thermal conduction, easily triggering unipolar arc and dust formation. Therefore test facilities are
needed to investigate the material properties of refractory metals from various points of view under reactor-relevant conditions. In order to investigate PWI under the high heat and particle flux we need to have a high plasma density of more than \(1 \times 10^{18} \text{ m}^{-3}\) with high electron energy. In this paper, a new plasma device for such PWI studies is introduced.

2. Device Specification

A unique plasma device has been constructed at the NRU "MPEI" for the study of plasma-surface interaction and the high-heat plasma testing of refractory metals, such as tungsten, molybdenum, steel and other plasma facing materials used in fusion reactor including the ITER. A machine view and machine structure are shown in Fig. 1. The diameter/length of the water cooling chamber is of 0.18 m/0.72 m. The magnetic system consists of solenoid, creating an axial magnetic field up to 8 mT on the axis, and permanent magnet bars that form the magnetic cusps along the axis (8-pole multi-cusps) providing stability of the plasma discharge. It is equipped with four pairs of neodymium permanent magnet bars comprising a 8-pole multicusp magnetic configuration and a solenoidal winding underneath the permanent magnets. Figure 2 shows the cross-section of the discharge chamber. Design parameters of stationary plasma discharge: discharge duration is up to 100 minutes or more, plasma current is up to 30A, plasma density is up to \(3 \times 10^{18} \text{ m}^{-3}\), electron temperature is up to 4 eV with an expected fraction of hot electrons up to 30 eV, ion plasma flux onto the metal test sample is up to \(3 \times 10^{21} \text{ m}^{-2}\text{s}^{-1}\), the working gas - helium, argon, deuterium. The cylindrical cathode with the diameter of 20 mm contains LaB6 ceramic elements mounted on the Ta support in the beginning zone of the magnetic field. The grounded anode made of copper is placed downstream in the middle position of the vessel and has a center hole of diameter 35 mm. It compresses the gas at the discharge region by a factor of \(~2\) due to a narrow gas channel. The gas compression is also enhanced by the plasma plugging. A higher plugging can be foreseen at higher discharge currents. The cathode-facing surface of the anode has a tapered structure. Heat removal from the inner wall is very important in such high-power and compact plasma devices. The main discharge chamber has a double-walled structure through which cold water flows ensuring efficient heat removal. The water supply of 5 l/min with a temperature rise of \(~10^\circ\text{C}\) removes \(~70\%\) of the power injected into the device, which is composed of discharge and cathode heating powers at the level of a discharge current of 30 A. Vacuum in the discharge chamber is produced by turbo-pumping of 500 l/s.

![Figure 1. (a) A view of plasma device. (b) Schematic of the device discharge chamber and magnet configuration: 1- cathode, 2- Ta shield of cathode, 3 – permanent magnets, 4 – solenoid windings, 5- copper anode, 6-steel ring support of the anode, 7 – radial port.](image)

3. Multicusp Magnetic Configuration
Multicusp magnetic configuration has been employed in many plasma devices starting from linear machines in 1960-th (see [3]), including compact plasma device AIT-PID [4,5] for the PWI studies. We have employed the eight-pole configuration. The eight-pole cusp gives a higher magnetic field barrier with a wide weak field space for plasma containment. Usually, a strong magnetic field of more than about 0.1 T is employed in linear plasma devices [7-12] for the radial confinement of the produced plasma. The electric power required for energizing the magnetic coils is very large. Contrary to this we use in our device not so strong magnetic field of less than 10 mT. Not only a power-saving compactness but also a favorable effect of eight-pole cusp gives the advantage of such device.

The axial magnetic field in the discharge chamber is created by a solenoid containing 50 windings on the chamber and made of insulated aluminum wire of 5x8 mm² cross section (see Figure 2). The solenoid is supplied by a stabilized power supplier. The temperature increase of the winding does not exceed 60°C at a current for solenoid up to 100 A. Figure 2a shows the axial magnetic field, which is of 6 mT at the axis for the solenoid current 50A. The flanges of the two sections of the discharge chamber and radial port give inhomogeneity winding along the vacuum chamber. As a result, there exists both the inhomogeneity of the axial and radial magnetic field. The magnetic field was measured and compared with the numerical analysis results (Fig.3). The axial magnetic field is analyzed numerically with the Biot–Savart formula. A permanent magnet is approximated by a single line magnetic dipole. The measurement showed good agreement with the numerical analysis.

The eight-pole configuration consists of 54 permanent magnets N45H of dimension 45x15x15 mm³ each, one bar consists of 9 such individual magnets. The magnetic moment of each of the magnets is about 2.6 \times 10^4 A-m². There are gaps of 10-20 mm between the individual magnets within a bar. This gap width is a compromise between the requirement to achieve the greater axial homogeneity of the field and the requirement to reduce the demagnetizing factor of the system. The positioning accuracy of the permanent magnet bars is on the order of 1 mm, it may not give a significant error in axial symmetry of magnetic configuration. The resulting magnetic configuration of such eight-pole system has all three spatial components. The preliminary measurements showed that near the wall of the discharge chamber it reaches a maximum of 0.2 T. Further detailed measurements and numerical simulations of the magnetic configuration will be done in the future.

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\text{Figure 2. (a) Axial magnetic field in the centre of solenoid downstream from the cathode location, for} & \text{the solenoid current of 50 A. (b) Cross-section of discharge chamber, double-wall (1), solenoidal} \\
\text{winding (2), series of permanent magnets (N-S), 8-pole magnetic configuration.} & \end{array}
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4. Discharge and experiments

We are focusing on the helium and argon gas for obtaining a discharge. To register plasma parameters and control the stability of the discharge the diagnostic systems such as Langmuir probes, bolometry system, spectroscopy, surface temperature measurements of the test targets are developed and manufactured.

A high density helium plasma is obtained for the helium ion irradiations on the ITER-grade tungsten, molybdenum and graphite. The tungsten target plate (20x20 mm²) is inserted into the central position of the discharge column. The present plasma generation device will provide the hot-electron component especially in He plasmas (as shown by experiments in AIT-PID device [4,5]), which gives a rather deep sheath potential so that a large ion incident energy on the target surface without any external biasing may ensure the formation of fiber-form nanostructure on tungsten surfaces, which is typical He defect due to PWI. The generation of a hot-electron component can be controlled by the gas pressure. Experiments are planned to develop a novel technology for highly porous surface structure of the refractory metal with a pore size and nanofibers of 50 nanometers including tungsten “fuzz”. Recently, microstructure of the tungsten surface was investigated after the test in tokamak plasma (Fig. 4a) and in pulsed heat load (Fig. 4b) modelling the ELMs in tokamaks. Strong erosion of tungsten surface was observed in tokamaks, Fig. 4,5, typically observed on plasma-facing components in large tokamaks (see [1]). The contribution of the arcs and sparks into the erosion process is discussed [1,2,13]. Such erosion was recently observed in the T-10 tokamak, Fig. 5a. The property of the arcs is specific in high-temperature plasma confined in magnetic field of fusion devices, such process contributes to the porous and roughen surface formation [13]. Droplets and nano-fibers can be produced by such surface and it can be the origin of the dust in the device [1,14,15], Fig. 5b. Such processes will be under investigation in our plasma device at NRU “MPEI” to obtain detailed and systematized experimental data on the plasma-wall interaction leaded to the erosion and formation of nanostructured surface.
Figure 4. (a) The SEM micrographs of the ITER-grade tungsten samples after the high heat plasma test in the T-10 tokamak. (b) Metallographic sections of the tungsten target after the high heat plasma test in the QSPA-T facility.

Figure 5. The SEM micrographs of the ITER-grade tungsten test sample from the T-10 tokamak: (a) arc’s erosion and (b) droplet formation.

5. Summary and Conclusion

We developed a unique plasma device aiming at plasma-wall interaction studies and plasma testing of refractory metals, such as tungsten, molybdenum, steel and other plasma facing materials used in
fusion reactor including the ITER. This plasma device is a multi-cusp linear plasma confinement system employing the 8-pole multicusp magnetic field configuration instead of a strong axial magnetic field. It has power-saving characteristics and compactness. The stationary plasma in this device makes possible the tests of materials under the high heat plasma load expected in stationary plasma of a fusion reactor. The aim of the work is to obtain detailed and systematized experimental data on the plasma-wall interaction and test of refractory materials. A physical model of stochastic clustering of a surface under the influence of plasma will be developed. Experiments are planned to develop a novel technology for highly porous surface structure formation of the refractory metal with a pore size and nanofibers of 50 nanometers including tungsten “fuzz”. Such research is actual for the inventing of new materials, which are of considerable interest for nuclear, chemical, energy, and biomedical technologies.

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