Tests of refractory and high-porous metals in plasma device at National Research University MPEI

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Abstract. The plasma device at the National Research University "MPEI" has been constructed within the scope of the National controlled fusion program to test materials for fusion reactors, namely, fusion neutron sources FNS, DEMO and the international fusion reactor ITER. The device is a plasma trap with a linear multicusp configuration of the magnetic field and stationary plasma discharge that provides high-power plasma thermal load on the samples under testing which are made of materials of the fusion reactor first wall. It is planned to develop a new technology for creating highly porous structure on the surfaces of refractory metals, including the so-called tungsten "fuzz" with diameters of pores and nanofibers of ~50 nm, which is of considerable interest for nuclear, power engineering and biomedical technologies.

1. Introduction
The plasma-surface interaction in fusion devices involves numerous processes of strong surface erosion, such as melting and resolidification of surface layers, melted material motion and sputtering over surface, sublimation, evaporation, redeposition of the eroded material over the surface, recrystallization, and variation of the surface layers thickness from tens of nanometers to hundreds of microns [1]. As a result, a structure of such surface obeys inhomogeneous hierarchical granularity (fractality), i.e., it is characterized by statistical self-similarity and scale invariance and its shape is unusual; e.g., recently, materials with cauliflower-like shape and fuzz-like surface were observed in fusion devices [1, 2]. Stochastic clustering of the surface has been recently detected in materials which were exposed to the extremely high plasma thermal loads in laboratory fusion devices [3, 4]. The plasma device at the National Research University "MPEI" has been constructed within the scope of the National controlled fusion program to test materials for fusion reactors, namely, fusion neutron sources FNS, DEMO and the international fusion reactor ITER. The device is a plasma trap with a linear multicusp configuration of the magnetic field and stationary plasma discharge with plasma parameters that provide high-power plasma thermal load on the samples of materials which is similar to that expected in the stationary plasma of a fusion reactor. At this facility with the stationary plasma discharge, formation of a nano-sized structures on surfaces of refractory metals (tungsten, molybdenum, titanium) was studied. In experiments, it is planned to develop a new technology for...
creating highly porous and highly corrugated structures on the surfaces of refractory metals, including the so-called tungsten "fuzz" with diameters of pores and nanofibers of ~50 nm, which is of considerable interest for nuclear, power engineering and biomedical technologies.

2. Plasma device

The plasma device is a linear system with the 8-pole multicusp magnetic field (Figures 1–3). Parameters of the device are as follows:

– longitudinal (axial) magnetic field at the axis of the coil is up to 0.01 T;
– magnetic field of permanent Nd magnets at the edge is 0.2 T;
– inner diameter of the vacuum chamber is 0.16 m;
– length of the discharge chamber is 0.72 m; the chamber is cooled by water that ensures a stable discharge regime.

Plasma parameters are:

– duration of plasma discharge is up to 100 min or more;
– plasma discharge current is up to 30 A;
– plasma density is up to $3 \cdot 10^{18} \text{ m}^{-3}$;
– electron temperature is up to 4 eV and there is a a fraction of hot electrons with energies of up to 30 eV;
– ion flow onto the metal sample under testing is up to $3 \cdot 10^{21} \text{ m}^{-2} \text{ s}^{-1}$.

Plasma heat load on the target samples under testing was more than 1 MW/m$^2$, and, in future experiments, we plan to increase the heat load up to 5 MW/m$^2$.

The working gases are helium, argon, and deuterium.

![Figure 1. Plasma device at the National Research University "MPEI".](image)
Figure 2. Schematic of discharge chamber (stainless steel) and magnetic system: (1) cathode, (2) tantalum screen, (3) permanent Nd magnets, (4) magnetic coils, (5) Cu anode, (6) stainless steel anode ring, and (7) diagnostic port.

Figure 3. (a) The multipole magnetic field contour plot; chromatic bar is graduated in Tesla. (b) Cathode and tantalum screen, system of gas inlet into the cathode region.

This facility is planned to be used for testing materials for resistance to destruction under the effect of the stationary hot plasma. Such studies will contribute to better understanding of the hot plasma interaction with such materials as tungsten, molybdenum, steel, and materials of the ITER first wall and divertor. The studies at this facility are topical due to detection of the increased erosion of tungsten in modern fusion devices and it is necessary to investigate this effect in full-scale experiments in order to clear up the physical mechanisms of erosion [1].

Combined tests of the water cooled tungsten modules of the ITER divertor are planned to be sequentially carried out in electron-beam and plasma devices: (1) thermocycling of the modules in the electron-beam facility with an electron beam load of up to 40 MW/m$^2$, and then (2) processing of the modules in the plasma device with stationary plasma loads of 0.5–1 MW/m$^2$ and higher. Such combined tests will be carried out for the first time. Such processing will simulate a varying load onto the divertor plates during the transient events in the ITER tokamak.
A series of experiments is planned to be conducted which are aimed at developing a technology for obtaining a highly porous surface of such refractory metals as tungsten, molybdenum and others, including the "fuzz"-type structure which is a unique structure formed from nanofibers with dimensions of up to 50 nm. The fuzz-like surface has a large specific surface area, which is of great importance for the adsorption of gases and catalysis. On such a surface, arcs can be easily ignited which strongly affects the plasma-wall interaction. Fuzz can be a source of nanodust which is considered to be a negative factor that causes radiation cooling of plasma in fusion reactors.

![Image](image_url)

**Figure 4.** (a) Helium plasma discharge and (b) plasma emission spectrum.

At present, the following facts are known concerning the formation of fuzz on the surface of tungsten details [5]: to create fuzz, it is necessary to process a tungsten surface in plasma by He$^+$ ions with energies of more than 20–30 eV; and the temperature $T$ of tungsten surface should be in the range of 1000–2000 K. The temperature range in which the fuzz can be created is determined by the following factors: at $T < 1000$ K, the adatoms concentration is so high and the distance between them is so short that clusters are formed rather quickly, and their transport to the top of the nanofibers is impossible; at $T > 2000$ K, the formation of clusters from adatoms is impossible because of their thermal decomposition.

The thickness of a fuzz layer increases with time as $t^{1/2}$, and, at an ion current density of $10^{18}$–$10^{19}$ atom/(cm$^2$ s), a fuzz layer of ~5 µm is formed during the time $t \sim 10^4$ s. Since the fuzz structure is formed under conditions of plasma processing at high temperature, the target should be pre-heated.

According to the theoretical estimates [5], when the tungsten sample is processed by helium plasma in the plasma device at the NRU “MPEI”, the tungsten temperatures should be in the range from 1385 to 1680 K.

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