Plasma device for material surface treatment by high-heat plasma

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Abstract. The plasma linear multi-cusp (PLM) device has been constructed to treat material surface by stationary plasma loads up to 5 MW/m². The PLM device is a plasma trap with the linear multi-cusp configuration of a magnetic field confined a stationary plasma discharge. It is planned to develop a new technology for creating a highly porous surface structure of refractory metals, including the so-called tungsten and molybdenum "fuzz" with pore size and nanofibers of ~ 50 nm, which is of considerable interest for material science, nuclear, power engineering and biomedical technologies.

1. Introduction

Strong erosion with stochastic clustering of a surface has been recently observed in materials under extreme thermal plasma loads in laboratory nuclear fusion devices [1-3]. The process of plasma-surface interaction in magnetic fusion devices involves several mechanisms of intensive surface erosion including melting and resolidification of surface layers, melted material motion over surface, sputtering, evaporation, redeposition of the eroded material on the surface, recrystallization, and reformation of surface layers from tens of nanometers to hundreds of microns [1]. In results, a structure of such surface obeys inhomogeneous hierarchical granularity (fractality) – statistical self-similarity and scale invariance of the surface structure with unusual shape; e.g., materials with cauliflower-like, figure 1, and fuzz-like surface recently found in fusion devices [1-4]. The plasma linear multicusp (PLM) device at the National Research University "MPEI" has been constructed [5] for material treatment by high-heat plasma. The device is used as well to test materials of fusion reactors – fusion neutron source FNS, DEMO fusion reactor and the international thermonuclear experimental reactor ITER. The PLM device is a plasma trap with a linear multi-cusp configuration of a magnetic field and a stationary plasma discharge with plasma parameters that provides a powerful plasma-thermal load up to 5 MW/m² on materials. At the facility with a stationary plasma discharge, investigations of a nanostructured surface formation on refractory metals (tungsten, molybdenum, titanium) will be carried out. In the experiments, it is planned to develop a new technology for creating a highly corrugated and highly porous surface structure of refractory metals, including the so-called "fuzz" with pore size and nanofibers ~50 nm, which is of considerable interest for material science, nuclear, power engineering and biomedical technologies.
Figure 1. (a) SEM micrograph of tungsten sample after irradiation by the high heat plasma in the QSPA-T facility [2-3]. (b) SEM micrograph of carbon film from the T-10 tokamak.

2. Plasma linear multi-cusp device - PLM
The plasma device PLM is a linear magnetic trap with a 8-pole multi-cusp magnetic field. Parameters of the device (figure 2–5) are as follows:
- longitudinal (axial) magnetic field on the axis of the coil – up to 0.01 T;
- magnetic field of permanent Nd magnets at the edge – 0.2 T;
- the internal diameter of the discharge vacuum chamber – 0.16 m;
- the length of the discharge chamber – 0.72 m, the chamber is cooled by water which ensures a steady state plasma discharge.

Plasma parameters:
- duration of plasma discharge – up to 100 min or more;
- plasma discharge current – up to 30 Amps;
- plasma density – up to 3×10^{18} m^{-3};
- the electron temperature – up to 4 eV with a fraction of hot electrons up to 30 eV;
- the ion plasma flow onto the metal test sample is up to 3×10^{21} m^{-2} s^{-1}.

Plasma heat load on test target samples – more than 1 MW/ m², experiments with a load of up to 5 MW/m² are planned.

The working gases are helium, argon and deuterium.
Figure 2. Plasma linear multi-cusp device – PLM.

Figure 3. Schematic of discharge chamber (SS) and magnetic system: 1 — cathode, 2 — tantalum screen, 3 — permanent Nd magnets, 4 — magnetic coils, 5 — anode, Cu, 6 — SS ring of anode, 7 — diagnostic port.

Figure 4. (a) Multi-pole magnetic field contour plot, colour bar in Tesla. (b) Cathode and tantalum screen, gas-inlet system into cathode volume.
This facility is planned to use for materials treatment with stationary hot plasma. Such studies will make it possible to advance the understanding of hot plasma interaction with materials such as tungsten, molybdenum, steel, materials of the first wall and the divertor of the ITER. The relevance of the work at this facility is related to the observation of increased erosion of tungsten in modern fusion devices that it is necessary to investigate in full-scale experiments to establish the physical mechanisms of erosion [1].

It is planned series of experiments aimed at developing a technology for obtaining a highly porous surface of refractory metals (tungsten, molybdenum and others), including the "fuzz" – type structure with a unique structure consisted from nanofibers of size of up to 50 nm. The fuzz surface has a large specific area, which is of great importance for the adsorption of gases and catalysis. On such a surface, arcs can be easily ignited leading to a strong effect on plasma-wall interaction.

Figure 5. (a) The helium plasma discharge, plasma current 0.8 Amps. Plasma load on tungsten test sample up to 0.3 MW/m². (b) Plasma discharge current vs. current in magnetic coil solenoid; line – a parabolic fit.
At present, the following is known about the formation of tungsten fuzz on the surface of tungsten [6]: to generate fuzz, it is necessary to irradiate a tungsten surface in the plasma with the energy of He + ions of more than 20–30 eV; the temperature $T$ of tungsten surface should be of $1000–2000$ K. The other temperature intervals: 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 transfer 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.

Figure 6. The helium plasma radiation spectrum.

Figure 7. Probe measurements in plasma: probe current vs. voltage. Plasma discharge current 15 A. Gas – He.
The thickness of the fuzz layer increases with time as \( t^{1/2} \) and at an ion current density of \( 10^{18} - 10^{19} \) He/(cm\(^2\) s), a fuzz layer of \( \sim 5 \) \( \mu \)m is formed during the time \( t \sim 10^4 \) s. Since the structure of the fuzz is formed under the plasma irradiation at a high temperature, the test target should be pre-heated.

According to the theoretical estimates [6], the temperature of tungsten from 1385 to 1680K under the irradiation with helium plasma is recommended for the PLM plasma device.

The experiments on the PLM device have been carried out. The cathode is made from tantalum wire heated up to 2680 K. The tantalum screen is used to increase the efficiency of cathode heating made from tantalum (figure 3b). The helium plasma discharge (figure 7) in the PLM has been investigated, discharge duration was from \( \sim 60 \) min to \( \sim 100 \) min in these experiments. Plasma current with tantalum cathode reached the value of more than 15 Amps (figure 5b), it has the parabolic dependance on longitudinal magnetic field (figure 5b). Anode was heated by plasma up to 450\(^\circ\) C during stationary plasma discharge. Current on the tungsten test sample of 2\( \times \)2 cm\(^2\) reached 2 Amps. Plasma load on tungsten test sample up to 1 MW/m\(^2\) has been reached in these experiments. Spectrum of the helium plasma radiation (figure 6) demonstrates dominant intensity of helium lines (figure 6), no impurities lines with high intensity were detected. It demonstrates low impurity level in plasma discharge. The plasma temperature evaluated from spectroscopic data was of 2 eV with a fraction of hot electrons with temperature up to 55 eV. Measurements by Langmuir probe has been made (figure 7). From current-voltage dependence (figure 7) the plasma density has been estimated which reached the value of \( 10^{17} \) m\(^{-3}\) in plasma discharge with plasma current of 15 Amps and longitudinal magnetic field of 6 mT.

3. Conclusion
The plasma linear multicusp (PLM) device at the National Research University "MPEI" has been constructed to treat materials including testing materials of a fusion reactors - fusion neutron source FNS, DEMO and the ITER. The device is a plasma trap with a linear multicusp configuration of a magnetic field and a stationary plasma discharge with plasma parameters that provides a plasma-thermal load up to 5 MW/m\(^2\) on materials. The first experiments with helium plasma has been carried out. Plasma load on tungsten test sample up to 1 MW/m\(^2\) has been reached in these experiments. It is planned to develop a new technology for creating a highly corrugated and highly porous surface structure of refractory metals, including the so-called "fuzz" with pore size and nanofibers \( \sim 50 \) nm, which is of considerable interest for material science, nuclear, power engineering and biomedical technologies.

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