Erosion of Fusion Materials under High-Power Steady-State Plasma Stream on the LENTA Facility

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Abstract. The LENTA linear plasma facility has been used to study erosion of plasma-facing materials (tungsten, graphites, CFCs) under deuterium plasma impact. The plasma stream propagated along the axial magnetic field through a gas target in steady state and simulated the conditions relevant to the ITER divertor channel. These are characterized by combination of a few eV plasma temperatures with a high divertor target surface temperature. This combination is obtained due to the plasma production method inherent in the LENTA where an electron beam generates the plasma with a few eV temperatures and the traversing beam portion provides the needed high surface temperature (1000-1500 K). The materials have been subjected to plasma exposure, the plasma parameters were Ne~10^{12}-10^{13} cm^{-3}, T_e~0.5-10 eV, the accumulated ion fluence ~10^{26} m^{-2}. Tungsten has shown the erosion effect at ion energies essentially lower than the energy threshold for the physical sputtering by deuterons. The subthreshold sputtering effect was explained by the sputtering of tungsten adatoms from the surface at high temperatures. Chemical erosion of carbon materials was observed both at high (>1200 K) and at room temperature for low energy plasma ions (5-10 eV). Influence of fusion neutrons on material erosion in plasma is considered on the basis of the modeling of neutron radiation damages with accelerated ions of MeV-level (to 1-10 dpa) and exposure of damaged materials to plasma.

1. Introduction

One of the ITER physics issues concerning power and particle control is the minimization of erosion during normal operation and transient events and related material choice. To date, carbon material (CFC) is adopted as a plasma facing material for the strike zone and tungsten for the rest of divertor. Among the divertor operation regimes, a detached plasma regime, which is characterized by a reduced ion current and reduced energy deposit to plate, is considered. Electron temperature falls down to around 1 eV in the gas target region in the divertor thus leading to enhancement of radiation and to reduction of energy flux to the plate. However, taking into account high heat load on the target at 5-10 MW/m^2 in steady-state and even more high level due to transitions which increase the heat flux, the necessity to investigate experimentally plasma induced erosion of the above materials in those conditions appears to be of a very high importance. The ITER divertor target is expected to operate normally at ion flux density of about 10^{24} m^{-2}s^{-1}, electron and ion temperature of few eV and it will have elevated surface temperature (~1000-1500 K). The surface temperature excursions exceeding these values are also possible in presence of transient loads (e.g. ELMs).

In the present work we report on the experimental study of tungsten and carbon materials under deuterium plasma impact in the LENTA linear plasma device, which simulates the plasma conditions in the ITER divertor channel close to the detached plasma regime. The LENTA device is a steady-state plasma generator in which the plasma is produced by the electron beam interacting with gas. Erosion of the materials is studied in the range of the very low bombarding plasma ions energy (≤ 10 eV) at elevated surface temperatures. To obtain the needed combination of the low temperature of the plasma contacting the target (1-3 eV) while maintaining a high target surface temperature (1000-1700 K) we use a feature inherent in

LENTA to produce plasma: the power required to achieve high surface temperature is provided by the rest portion of the e-beam traversing the plasma column. Note that in other similar facilities one has to apply an appropriate bias to obtain high surface temperature in the low temperature plasma (PSI-2, PISCES-B, NAGDIS), which not only gives rise to the power load but also increases the ion impact energy thus distorting the conditions under study.

2. Experiment

LENTA is a steady-state plasma device [1] with a beam-plasma discharge (BPD) as the basic method of plasma production. The schematic of the facility is shown in Fig.1. The plasma operates with a constant axial magnetic field 0.1-0.2 T in the discharge zone. The beam-plasma discharge is the source of a plasma stream and is exited in the discharge zone by an electron beam, which is formed with an electron gun placed on the axis at one end of the vacuum chamber. The gun has a tungsten hot cathode of 20 mm diameter and a molybdenum water-cooled anode. Electrons are accelerated by the voltage 1-6 keV and the current varies at 0.1-3 A. The plasma is formed due to interaction of the electron beam with primary gas introduced into the discharge zone. Here, the plasma absorbs the most of the beam energy. Parameters and radial structure of the plasma depend on the chosen mode of the discharge: BPD in magnetic field or BPD in crossed E×B fields (when radial E-field is applied). The present experiments have been performed in the first mode. In this case cylindrical plasma column was of about 2 cm diameter in the discharge zone. The plasma stream flowed along the magnetic field to the next section where gas target was formed by feeding a secondary gas at higher pressure corresponding to tokamak divertor. Differential pumping system (turbo-molecular pumps, Roots pump) provided the necessary pressures all over the length of the facility from $1\text{-}10^{-3}$ Torr in the gas target to 10^{-5}- 10^{-6} Torr in the electron gun. The plasma stream interacted with the gas target and terminated at the end collector (target) which was actively cooled. Examples of material samples positioning are also shown in Fig.1.

Plasma parameters were measured with a set of Langmuir probes movable in radial direction and placed in different points along the axis. Optical monochromator, isotope mass-spectrometer were used to analyze the optical radiation and gas composition during the plasma operation and exposure of material samples. Calorimeter has been also applied to measure heat deposition on the target. Temperatures of different units and of the samples under study were detected with thermocouples and with optical pyrometer.

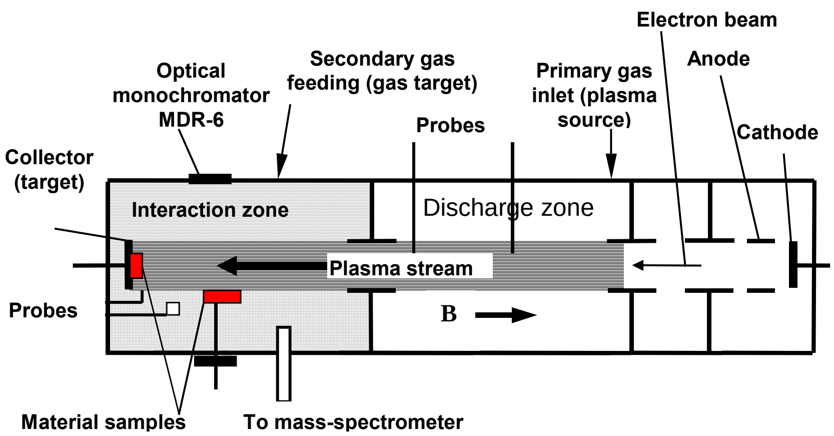


FIG. 1. Schematic of the LENTA linear plasma device with material samples.

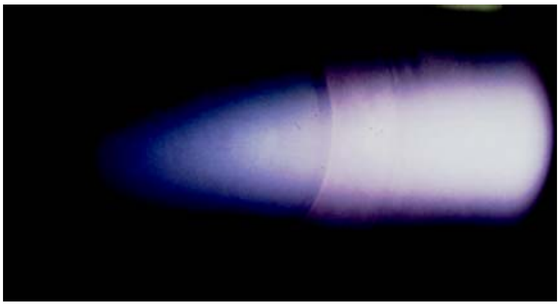


FIG. 2. Detached plasma in the LENTA experiments. Target is on the left hand side of the photo.

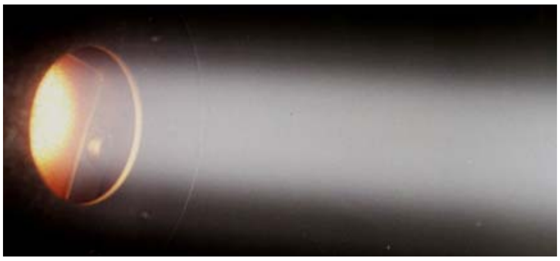


FIG. 3. Graphite sample under deuterium plasma impact.

Experimental simulation of gas divertor conditions has been made in the LENTA facility prior to material tests and the detailed data have been obtained (the results were reported elsewhere [1]). It was shown namely that while plasma in the disharge zone had an electron temperature of T_e ~ 4-8 eV it fell down to 0.5-2 eV at the target position depending on the secondary gas pressure and initial plasma parameters. Typical plasma density in the discharge zone was $N_e \sim 10^{12}$-10^{13} cm^{-3}. Plasma density decrease towards the target was also observed in appropriate choice of the parameters. The picture of plasma detachment is shown in Fig. 2.

The samples were placed both at the end target and beside the plasma column. Biasing possible on the target and lateral samples was not used in these experiments. Shown in Fig. 3 is a view of a graphite sample 3×4×1 cm disposed at the end target during exposure to deuterium plasma. The temperature in the hot spot of the shown sample is 1300 K.

A microstructure analysis of the target surfaces was made using the JEOL scanning electron microscope. The weight loss was measured to evaluate erosion yield with the account for the measured accumulated ion fluence. The chemical composition of the exposed targets was determined by Rutherford backscattering (RBS) analysis using the Van de Graaf accelerator in which 2-MeV protons backscattered at 160^o were detected with a surface barrier detector. Phase composition of the targets after irradiation was determined by X-ray diffraction analysis using the DRON-4 diffractometer. We used the Elastic Recoil Detection Analysis to study the D content in the specimens. To this end, a beam of He^+ ions with an energy of 2.2 MeV was directed at 15^o to a specimen's surface. The recoil atoms were registered at 30^o to the initial He^+ ion incidence angle.

3. Results and discussion

Erosion of tungsten at high temperature. Tungsten is a candidate ITER armour material.

It has a calculated sputtering threshold by deuterons equal to 201 eV and experimentally measured one at 160-180 eV [2]. Therefore it is expected to suffer erosion only during disruption events. However we have recently observed tungsten erosion losses in deuterium plasma in stationary conditions for the ion energy below 10 eV at the surface temperature $T_{surface}$=1470 K [3,4]. The energy of the ions striking the surface was determined in our experiments by sheath potential. In simulated gas divertor conditions we had electron temperature about 1.5 eV. A potential drop in deuterium plasma contacting the surface is usually assumed to be 3-3.5 T_e, so that the results were obtained for ion energy of about 5 eV. In our case we obtained space potential by direct measurements from current-voltage characteristics of Langmuir probes providing values of potential drop at the surface. Given in Fig. 4 is a typical probe characteristics taken in the gas target region (2 mTorr) in deuterium plasma stream. The kink of the electron part of the curve corresponding to the space potential is here about 5-7 eV.

The first observations of the subthreshold sputtering were made on W–0.04Mo specimens at ion flux density (1-5)·10^{21} $m^{-2}s^{-1}$. Fig. 5 shows surface microstructure of the samples before and after exposure. Erosion yield has been evaluated to be 1.5·10^{-4} at/ion [4]. These experiments have also shown relation between the effect and the surface temperature: no surface changes have been found below 1070 K [4].

To study the found effect in more details we took four other tungsten grades and performed experiments with samples made of W-1%La_2O_3, W-13I, W-10Re and W⟨111⟩. Deuterium (D)

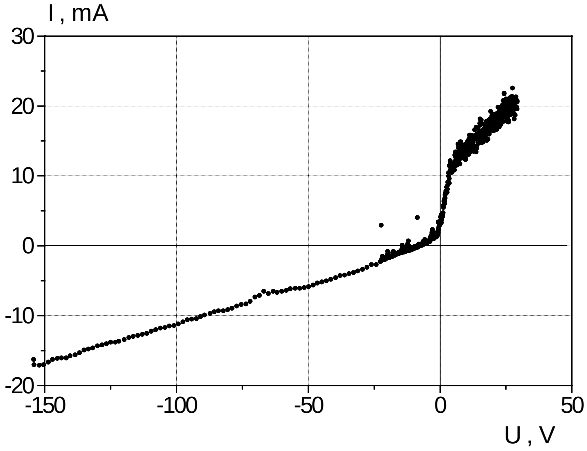
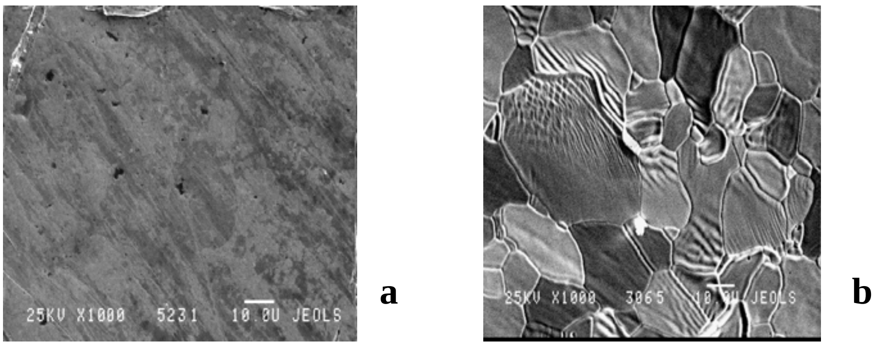
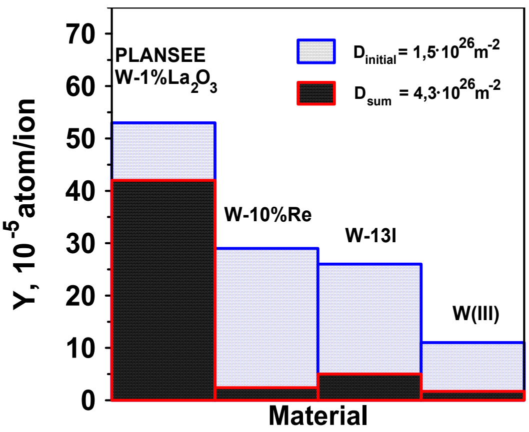


FIG.4. Typical current-voltage characteristic of Langmuir probe in gas target region (deuterium plasma, T_e = 2 eV, N_e = 1·10^{12} cm^{-3} , 2 mTorr).



FUG. 5. Surface microstructure of tungsten samples before (a) and after exposure (b) to deuterium plasma at $T_{surface}$=1470 K to the ion dose 10^{26} m^{-2} (scale marker 10 µm).



W grade	Y_1 (at/ion)	Y_2 (at/ion)	Y_1/Y_2
W-1La_2O_3	5.3×10^{-4}	4.2×10^{-4}	1.3
W-10 Re	2.9×10^{-4}	2.4×10^{-5}	12.0
W-13I	2.6×10^{-4}	5.0×10^{-5}	5.2
W⟨111⟩	1.1×10^{-4}	1.7×10^{-5}	6.5

FIG. 6. The ion dose dependence of a subthreshold sputtering yields for different W grades.

plasma flux density was maintained at 1.1×10^{22} $m^{-2}s^{-1}$, the deuteron energy was again about 5-7 eV. The temperature of the target samples was set in the range of 1300–1600 K. The four test specimens were irradiated in the plasma simultaneously being placed in the equal plasma condition in the plasma column. There were two irradiation runs with these specimens. The ion dose accumulated during the first run was $F_1 = 1.5 \times 10^{26}$ m^{-2} while the second exposure gave additional fluence of $F_2 = 2.8 \times 10^{26}$ m^{-2} so that the cumulative value became 4.3×10^{26} m^{-2}. After each irradiation run, the sputtering yield was evaluated for each specimen under study (Y_1 and Y_2). The results of this series are shown in Fig. 6.

The sputtering of tungsten by low energy D^+ ions in dense deuterium plasma took place for all the W grades under study. The sputtering yield values depend on a W grade. As one can see from the table, the sputtering yields for all the W grades tend to decrease with the increasing dose. The smallest Y_2 (1.7×10^{-5} at/ion) was observed in the case of single crystal W⟨111⟩ and the greatest one (4.2×10^{-4} at/ion) – in the case of a La_2O_3-doped sintered W grade. The surface microstructure was also studied by SEM analysis. Modification of the surface has been revealed: a submicron structure (150-300 nm) was found to appear on the surface at higher doses for all tungsten grades (see Fig. 7).

The mechanism of W subthreshold sputtering, based on potential sputtering of adsorbed W atoms that are released from interstitial traps and come onto target surface from the intergranular space at high temperature, has been detailed in [3,4]. Neither RBS nor X-ray diffraction analyses have revealed any admixtures or chemical compounds in the surface layers of the W targets following their exposure to the plasma. Therefore the observed modification of the surface morphology of all the W targets must be due to some processes affecting W surface. It has been known [5] that at high irradiation doses, sputtering yield depression and surface relief modifications are largely attributable to the migration of individual atoms and the sputtered atom redeposition. Under simulated gas divertor conditions, at an elevated neutral D pressure and a temperature of ~ 1500 K, the surface relief evolution and the ensuing sputtering decrease are evidently driven by a combination of processes, namely, the sputtering of adsorbed atoms (adatoms), their surface migration, and redeposition taking place at a time. The ion dose dependence of the observed sputtering is believed to have to do with the depletion, with time, of adatom reserves in irradiated materials.

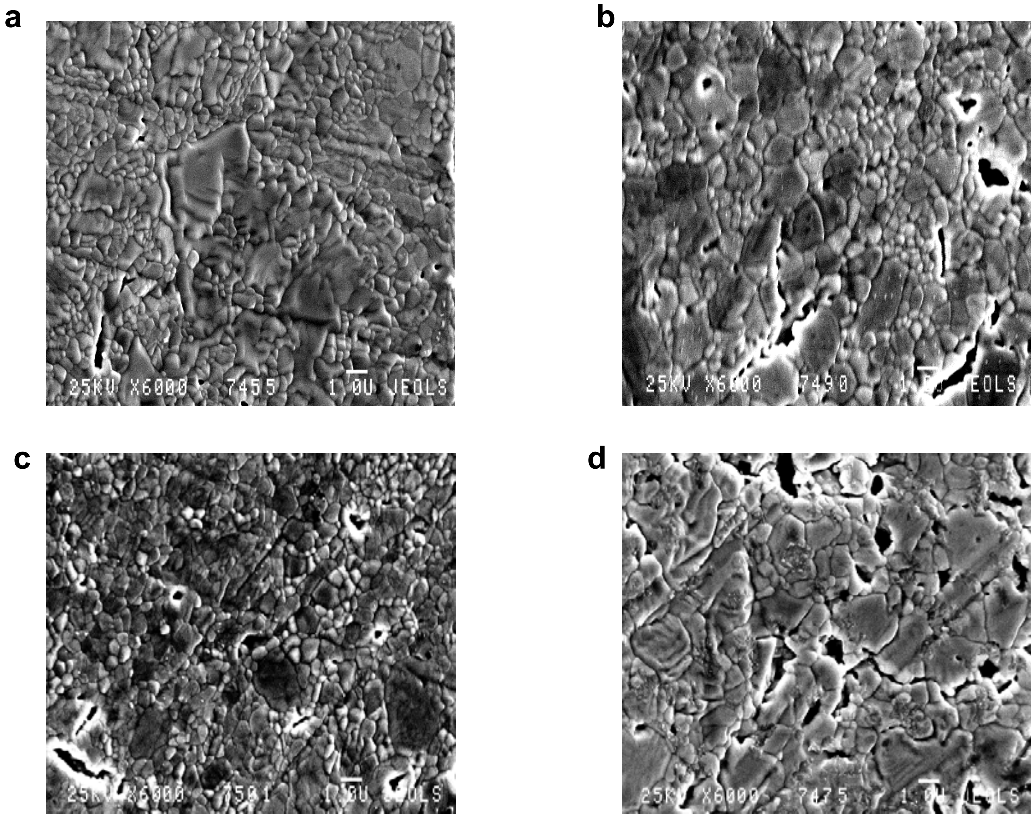
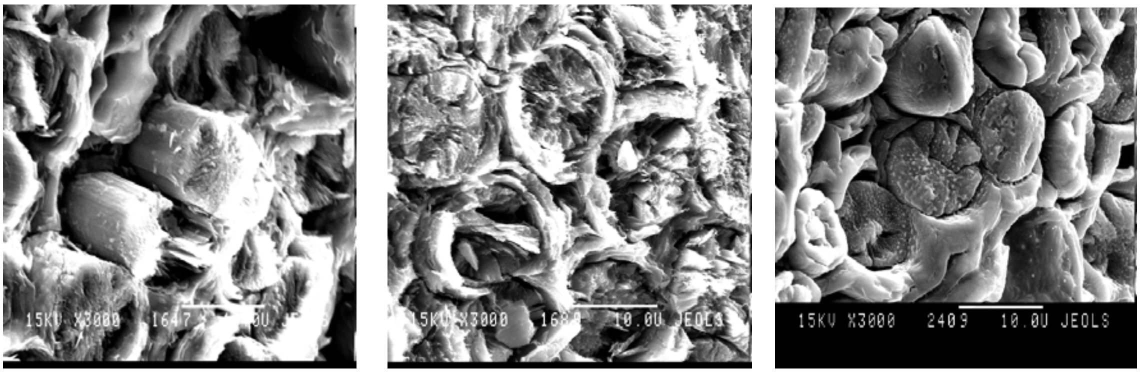


FIG. 7. Surface microstructure of W-10Re (a), W⟨111⟩ (b), W-13I (c) and W-1%La_2O_3 (d) after their irradiation by 5-eV D^+ ions in D plasma at 1470-1520 K with cumulative ion dose $F_\Sigma = 4.3 \times 10^{26}$ м$^{-2}$(scale marker 1 μm).

One may suppose that the observed ion-dose-dependent reduction of the subthreshold tungsten sputtering yield makes this erosion effect negligible in the ITER conditions. However, erosion of materials by melting, evaporation and cracking during disruptions may promote the formation of adatoms in W target. This is confirmed by our observation of ~20% enhancement of erosion of W-13I, W-10Re and W single crystal after disruption simulated pulses on these samples. Moreover, the erosion may be enhanced by a synergetic effect of simultaneous exposure of a W target to plasma and to fast neutrons generating defects. Therefore, the effect of subthreshold sputtering experimentally observed in W-based targets may increase tungsten erosion rate in real-life ITER materials. This presumption leads us to the necessity to look further into the observed effect taking into account the combination of destroying processes inherent in a fusion reactor.

Erosion of carbon-based materials. Chemical erosion leading to tritium retention is an important issue for application of carbon-based materials in fusion reactor. We have studied erosion of MPG-8 Russian graphite and the ITER candidate CFC grade SEP NB 31. We have detected erosion of these materials in deuterium plasma at low energy of ions 5-10 eV. The evidence of chemical process was given by taking mass-spectra of the working gas during exposure of the carbon targets. Generation of CD_4 and its products (M/e = 18, 16 и 14) and of higher deuterocarbons C_2D_2 and others (M/e=30, 34, 36) has been found. The measurements were performed in the following conditions: plasma flux density (1-2)·10^{21} m^{-2}s^{-1}, the deuteron energy about 5-10 eV, ion fluence (0.5-1.1)·10^{22} m^{-2}, electron temperature 1-3 eV, surface temperature 1240-1470 K, neutral gas pressure at the target region 3-7 mTorr. The



a ***b*** ***c***

Fig. 8. SEP NB 31 surface before plasma exposure (a), after deuterium plasma to dose $0.6\cdot10^{22}$ ion m^{-2}, LENTA, (b) and then followed by disruption simulated in powerful pulses, MKT, (c)(scale marker 10 μm).

erosion yield was evaluated at $1.7\cdot10^{-2}$ at/ion for MPG-8 and at $(0.9\text{-}1.1)\cdot10^{-2}$ at/ion for SEP NB 31. Moreover, we have observed an important enhancement of the SEP erosion to $2.6\cdot10^{-2}$ at/ion in the case when the samples irradiated, first, in the steady-state plasma to the above dose were subjected, second, to simulated disruptions in powerful pulsed plasma (MKT facility, Troitsk) and then again to steady-state exposure, third. Fig. 8 shows the initial surface of the SEP sample before irradiation (8a), after steady-state plasma run (8b) and after the following disruption load (8c). The resulting enhancement of erosion after these plasmas is supposed to be due to the peculiar surface structure of the CFC. Finally, we have observed chemical erosion of the MPG-8 and SEP at low temperature of the exposed samples in similar deuterium plasma conditions. In this case the erosion yield was measured at $1.1\cdot10^{-3}$ at/ion for MPG-8. Note that our measurements don't correspond to the ordinary assumed maximum of chemical erosion by deuterium for graphites (600-900 K). We suppose that the erosion of the carbon materials in our experiments is due to high efficiency of chemical reactions at low energy of the plasma particles.

Erosion of materials with radiation damages. Plasma facing materials are subjected in a fusion reactor to high power heat and particle fluxes and to fusion neutrons as well. Neutron irradiation of the materials (14 MeV for DT) causes significant modification of their crystal structure and accumulation of radiation-induced damages in them. The level of the effect may achieve hundreds dpa. Up to now plasma erosion has been extensively studied on the materials having no radiation damages. However, we suggest that the erosion process will follow another way in the materials having neutron-induced damages rather than in undamaged materials. One could investigate the influence of radiation damages on plasma erosion of materials having a source of fusion neutrons, which still does not exist. Another possibility is irradiation of materials in a fast nuclear reactor, but it would take about two years to accumulate a dose necessary to obtain the level of few tens dpa. To bring the problem of such an investigation to a reality we have elaborated the following experimental procedure.

The effect of fast neutron irradiation is simulated with energetic ions. For this purpose we use the Cyclotron at Kurchatov Institute accelerating ions of different kinds to energies of 1-30 MeV. These ions produce damages at the level of tens dpa in a few days and this is equivalent to irradiation with fast neutrons to 10^{26} neutron/m^2. The study is performed in three stages: first we irradiate a sample by fast ions on the Cyclotron to obtain 1-10 dpa of damages; second, the sample suffer exposure to the steady-state plasma on the LENTA facility to induce erosion; third, structure modification of material and surface composition are analyzed. At the first step the following materials are taken for the study as the targets: pyrolytic graphite (as a reference grade), MPG-8 graphite (Russian grade) and CFC SEP NB. Carbon ions of 5 Mev are chosen for the bombardment in the Cyclotron to produce damages. The irradiation experiment has started.

4. Conclusions

1. Erosion of tungsten and carbon materials MPG-8 Russian graphite and the ITER candidate CFC grade SEP NB 31 has been investigated in linear plasma device LENTA in simulated gas divertor conditions at high surface temperature (1000-1600 K).
2. The effect of subthreshold tungsten sputtering by low energy D ions (5-10 eV) has been found to occur on exposure of W-based materials W–0.04Mo, W–10Re, W–1%La_2O_3, W–13I and single crystal W⟨111⟩ to a dense deuterium plasma at temperatures over 1070 K. Tungsten surfaces were modified at ion doses $\geq 10^{26}$ m^{-2} and exhibited submicron structure.
3. The subthreshold sputtering yields Y of plasma tungsten targets were found dependent upon the material grade and ion dose. The lowest value (1.7×10^{-5} at/ion) was observed in the case of single crystal W⟨111⟩ and the greatest one ($5.3 \cdot 10^{-4}$ at/ion) – in W–1%La_2O_3. Decrease of Y was shown for the ion dose rising from $1.5 \cdot 10^{26}$ to $4.3 \cdot 10^{26}$ m^{-2}.
4. The subthreshold sputtering of tungsten has found explanation by sputtering of adatoms present on the surface and by possible sources of their regeneration. The observed effect may have an influence on the service life of plasma facing armour taking into account that transient plasma events and fast neutrons can lead to structure damages promoting the adatom generation.
5. Chemical erosion of MPG-8 graphite and CFC SEP NB 31 was observed in plasma exposure at low ion energy (5-10 eV) both at high surface temperature (over 1200 K with Y=$1 \cdot 10^{-2}$ at/ion for CFC) and at room temperature. Enhancement of the erosion was seen by 2.6 fold after combined irradiation in steady-state plasma followed by disruption simulation.
6. Experiment is undertaken to investigate plasma erosion of materials having radiation damages. At the first step radiation damage is obtained by irradiation of carbon materials with energetic C-ions (5 MeV) to 1-10 dpa. The second stage is plasma exposure of these materials to determine erosion surface characteristics.

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