Application of a Plasma Accelerator of the Dense Plasma Focus Type in Simulation of Radiation Damage and Testing of Materials for Nuclear Systems

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Abstract. We present some results of our experiments with use of a number of plasma accelerators of the Dense Plasma Focus type, namely PF-5M (IMET, bank energy – 5 kJ), PF-6 (IPPLM, 7 kJ), and the largest in the world DPF facility operating with deuterium as a working gas PF-1000 (IPPLM, 1.2 MJ). We use this set of devices for application in the field of radiation material sciences, in particular for Simulation of Radiation Damage and Testing of Materials intended for use in Thermonuclear Reactors (TNR) of both types – with magnetic plasma confinement (MPC) and with inertial plasma confinement (IPC). These devices can produce *directed streams* of the same types of radiation and having the same parameters (density, temperature, spectrum, energy of fast particles, etc.), which are expected on the walls of the reactors' chambers. It is independent on DPF bank energy (it is clear that we can ensure the above parameters on different areas of a sample). Power flux density of plasma and fast ion/electron streams on the sample's surface during the experiments, which simulate conditions on plasma-facing components inside thermonuclear fusion reactors, may reach on the target's surface (on the face of a specimen under test) as much as 10^{10} W/cm^2. It is about those expected in the reactors with the inertial (IPC) plasma confinement and much higher than those with the magnetic plasma confinement (MPC). We describe results on the interaction of powerful deuterium plasma and fast ion/electron streams with specimens made of tungsten and carbon-fiber-composites, which are counted as a candidate materials for use as plasma facing and construction components of TNR with MPC and IPC. In our analysis of the irradiation consequences we apply optical, scanning electron and atomic force microcopy, X-Ray elemental and structure analysis, etc. Taking into consideration that the above materials are the main construction and plasma facing resources for ITER and NIF facilities, the results received are fruitful for estimations of prospects of their use in these reactors as well as in the next generation of fusion reactors. Some recommendations on the use of these materials will be presented.

1. Introduction

The behavior of different plasma faced materials in thermonuclear fusion reactor under irradiation in extreme conditions is of great interest in connection with realization of international projects Iter [1] and NIF [2]. They are related to powerful thermonuclear fusion devices with magnetic plasma confinement (MPC) and inertial plasma confinement (IPC). Formerly [3, 4] we have shown the advantage of Plasma Focus devices (DPF) for simulation of heat loads and for investigation of damage of divertor's and first wall materials in thermonuclear fusion reactor with MPC at extreme conditions of the types of plasma disruption or ELMs effects.

The work is aimed to investigate the main features of damage of tungsten and composite material CFC (carbon fiber composites) produced by powerful pulsed high energy ion beam and dense plasma stream in DPF device. Sample materials W and composite material CFC are considered usually as the main materials for divertor in the ITER project. Samples of W and CFC were irradiated at conditions closed to extreme cases in ITER as well as at more hard conditions closed to ones expected for thermonuclear fusion reactor with IPC.

2. Materials and radiation conditions

Specimens (10x10x2) mm of sintered W with impurities (Fe, Ca, C, N, H, O up to 0.05%) were prepared at A.A.Baikov Institute of Metallurgy and Material Sciences (IMET), Russian Academy of Sciences. Specimens of the composition W/CFC 25x25x10 mm (CFC sample with shrunk-in W cylinder ∅ = 12 mm) were prepared in KFA, Julich (Germany). CFC material reinforced with SiC particles up to 8 and 40 vol. % (10x10x8) mm was prepared in Royal Institute of Technology (Stockholm, Sweden).

W and W/CFC specimens irradiated were fixed on the steel rod with different distances from anode of DPF device PF-1000 (Fig. 1). CFC/SiC specimens were fixed at steel holder, which was fixed on the end of the rod located along the axis of DPF. Pulsed irradiation of specimens was performed in the following regimes: power flux density $q = 10^7 - 10^{10}$ W/cm^2, pulse duration $\tau = 0.2$ - 1 μs, energy stored in the DPF bank was ~ 600 kJ. Deuterium was used as a working gas under initial pressure of 470 Pa. The specimens of W and W/CFC were irradiated with N = 10 pulses in series whereas the specimens of CFC/SiC – with N = 5.

Some experiments with selected materials were performed using DPF devices PF-5M (IMET), bank energy of 5 kJ) and PF-6 (Institute of Plasma Physics and Laser Microfusion (IPPLM), 7 kJ).

3. Results and discussion

3.1 The surface damage of tungsten

The analysis has shown that pulsed irradiation was resulted in melting and evaporation of tungsten surface layer with a formation of a typical wavelike surface relief (see Fig. 2, 3). In Fig. 3 one can see zones with nanoscale cellular structure, which were observed under $q = 10^{10}$ W/cm^2. There are a lot of droplets and highly long microcracks on irradiated W surface. With high power density $q > 10^8$ W/cm^2 not only intergranular but also transgranular microcracks were observed. The propagation of microcracks into bulk of material was not as significant as it was along the surface. It had a size of few microns. But in some parts of the surface layer the microcracks penetration inside the material was ~ 10 μm or more. It was observed in those areas where grains were elongated normally to the surface (see Fig. 4). Under power flux density $q > 10^8$ W/cm^2 both intergranular and transgranular microcrack formation were observed.

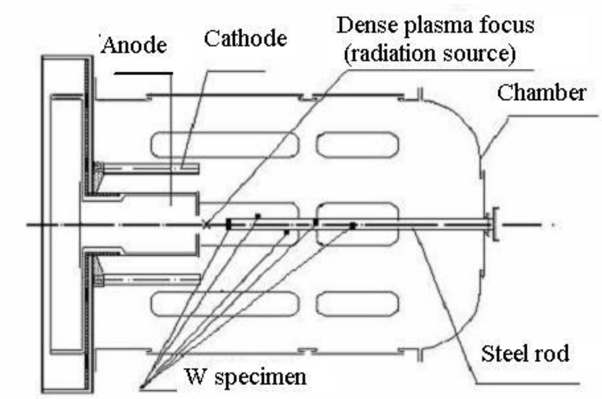


FIG.1. Scheme of the experiments in the PF-1000

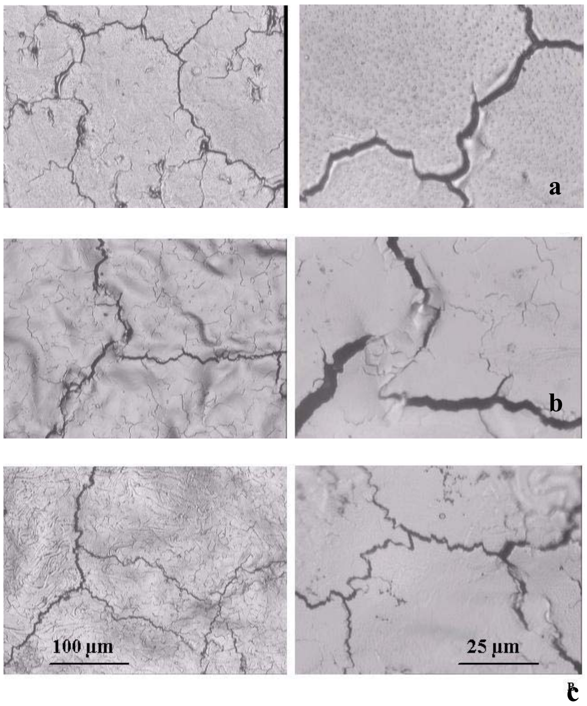
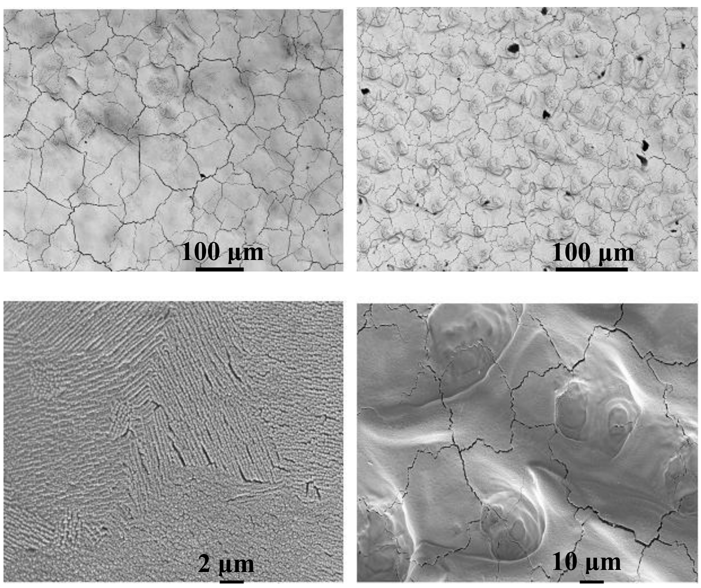


FIG. 2. Microstructure of sintered W after irradiation (10 pulses): ***a*** *- q = 8·10^{7} W/cm^{2},* ***b*** *- q = 2·10^{8} W/cm^{2},* ***c*** *- q = 10^{10} W/cm^{2}; optical microscopy*

On some parts of irradiated W surface the aggregate of bubbles was observed (see Fig. 5). Typical size of the bubble was of the order of 1 µm. We suggest that gas phase in the bubbles contains implanted deuterium and volatile compounds of deuterium with contamination elements of initial material (C, N and O).



a **b**

FIG.3. Microstructure of W in W/CFC composition after irradiation (10 pulses): ***a*** *- q =* 10^{10} W/cm^{2}**,** ***b*** *- q* = 3 · 10^{8} W/cm^{2} *(scanning electron microscopy) [5, 6]*

The analysis has shown, that irradiation of material was resulted in the erosion connected with mass loss and reduction of the specimen thickness in comparison with the source state. For the specimens irradiated with power density q ~10^8 W/cm^2 the erosion depth d was of hundredth parts of micron (see table 1). Under the highest power density q = 10^{10} W/cm^2 erosion depth d was approximately two order of magnitude higher (2μm). The results obtained are useful for preliminary express estimation of material behavior in extreme conditions of the type of plasma disruption or ELMs effects in Iter.

Ion and plasma beam irradiation was result in ion implantation of working gas and elements of materials placed inside the DPF chamber within the surface layer of W. In the surface layer beside W we observed such elements as Cu, O and components of the steel. Ferrum and Chromium were parts of structural materials placed in PF-1000: cathode tubes, steel holder for W specimens, *et al.* The copper anode of PF-1000 contains oxygen as a contamination. Cu, Fe, Cr and O evaporated and sputtered by electron (on the anode), ion and plasma beams were deposited on the surface of W specimens. Under multifold pulsed irradiation the deposited elements were mixed in liquid phase and penetrated inside the surface layer.

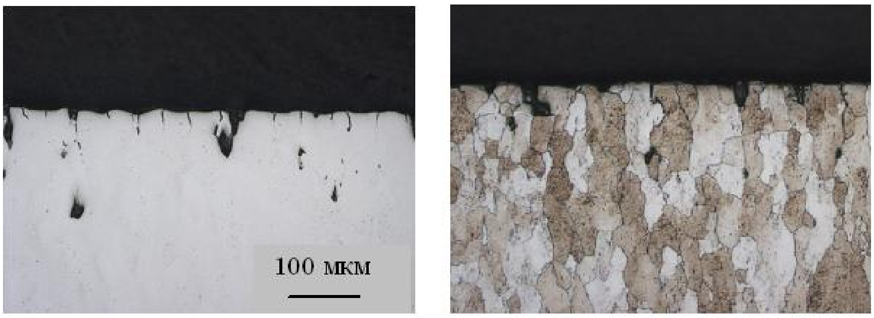
It is important to have in view the complex action of working gas ions and evaporated (sputtered) elements of structural materials of DPF device when tungsten is considered as material for divertor in Iter as well as alternate material for thermonuclear fusion reactor with inertial plasma confinement.

3.2 Damage of CFC material in W/CFC composition

Fragments of solidified W in form of droplets and elongated ridges on the surface of CFC material after irradiation at q = $3 \cdot 10^{10}$ W/cm^2 are presented in Fig. 6. These fragments were deposited on CFC surface after explosive action of pulsed energy stream. Carbon fibers of CFC material were evaporated more significantly when the fiber was normal to irradiated surface (see Fig.7).

3.3 CFC/SiC material

The microphotograph of CFC-8SiC material in an initial state and after an irradiation by pulses of energy is presented in Fig. 8. Damage of the surface layer under deuterium ions and plasma irradiation was attributed to evaporation and sputtering. Structure of the material was steady under deuterium plasma irradiation in hard conditions. *It is significant positive property of considered composite material for application in divertor of Iter.*



a **b**

FIG. 4. Cross-section microstructure of W specimen in W/CFC composition after irradiation (10 pulses): $q = 3 \cdot 10^8$ W/cm^2, ***a*** *– unetched surface,* ***b*** *– etched surface [5, 6]*

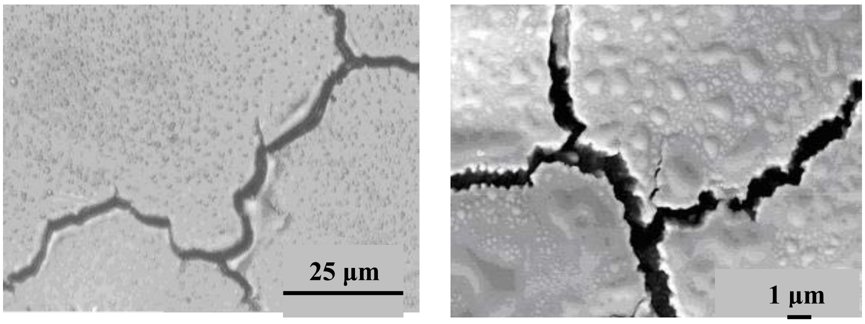


FIG. 5. Formation of bubbles on the irradiated W surface ($q = 3 \cdot 10^8$ W/cm^2, 10 pulses)[5,6]

TABLE I: EROSION OF THE TUNGSTEN

Specimen #	1	2	3	4	5	7
Power density q, 10^8 W/cm^2	0. 5	0. 8	1	2	4	10^2 ions 10^1 plasma
Erosion depth per one pulse d, 10^{-2} µm	—	1. 23	2. 67	6. 96	3. 90	205

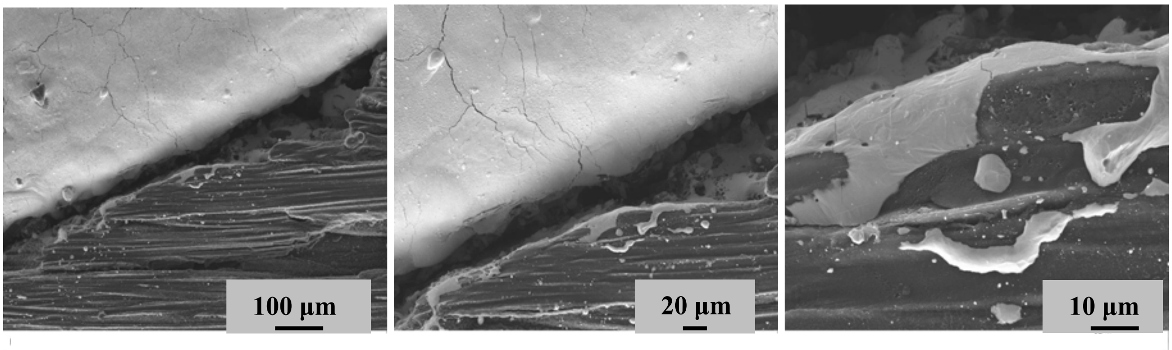


FIG. 6. Contact zone between W and CFC after deuterium ion and plasma beam irradiation ($q = 10^{10}$ W/cm^2, 10 pulses) [5, 6]. Carbon fibers are parallel with surface irradiated

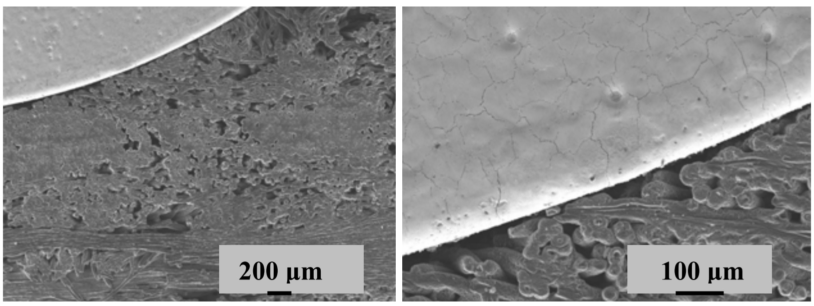
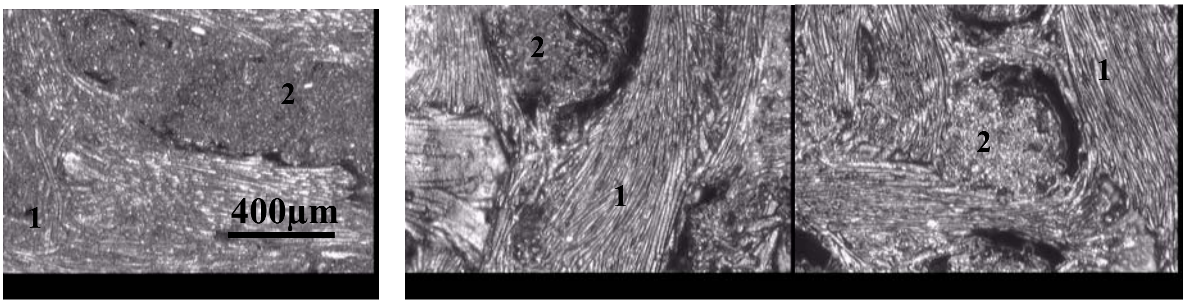


FIG. 7. Contact zone between W and CFC after deuterium ion and plasma beam irradiation ($q = 3 \cdot 10^8$ W/cm^2, 10 pulses) [5, 6]. Carbon fibers are normally to surface irradiated



a **b**

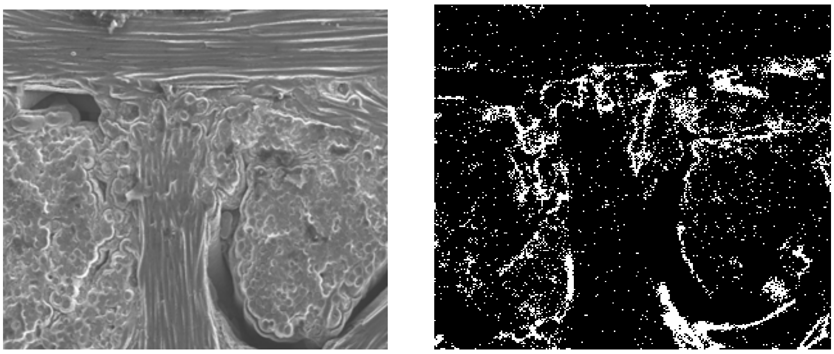
*FIG. 8. Composite material CFC-8SiC in initial state (**a**) and after irradiation (**b**): $q = 10^9$ W/cm^2, 5 pulses; 1 – fibers are in parallel with irradiated surface, 2 – fibers are normally to irradiated surface*

The table 2 presents estimation of evaporated layer thickness d for considered composite under irradiation with deuterium ion and plasma pulsed beams when carbon fibers of CFC material were oriented in parallel to the beam. The results show that under power flux density $q = 10^9$ W/cm^2 the thickness of evaporated layer d was about two or more microns. It is sufficiently higher value in comparison with sintered W and ferritic steel type of Eurofer 97 [4]. For these materials the thickness of evaporated layer d was about 2 µm at power flux density one order of magnitude higher. If the fibers of CFC material were in parallel with irradiated surface then the erosion rate was remarkable lower. *The influence of the carbon fibers orientation upon erosion rate of CFC/SiC composite under high energy beams should be taken into consideration when it will be applied as structural or functional material in devices of the type of plasma accelerator and thermonuclear fusion reactor.*

TABLE 2: EROSION OF THE CFC/SiC MATERIAL

Type of material	Power flux density, q, W/cm^2	Number of shots, N	Thickness of evaporated layer (per one shot) d, µm
CFC – 8SiC	10^9	5	2,6
CFC – 40SiC	10^9	5	1,9

In initial state SiC particles are displaced in CFC composite mainly in zone between fiber bundles (see Fig. 9). After ion-plasma action the Fe, Cr, Si and Cu were observed on the irradiated surface (Fig. 10). The presence of these elements is connected with evaporation of steel holders (Fe and Cr) and anode (Cu) and with the following-up re-deposition of them on the target surface. Deposited atoms under multifold shots were embedded into the surface layer. Disperse compounds of the type of carbides and intermetallides (Fe_2C, Fe_5C_2, Cu_4Si, $(Cr,Fe)_7C_3$) were presented in the surface layer with thickness of few µm. The appearance of these compounds may result in lattice distortion, which will affect the composite CFC/SiC diffusion permeability of deuterium in combination with thermal lattice distortion in the surface layer after action of high energy pulsed beams.



a **b**

*FIG. 9. Second electron image (**a**) and distribution of characteristic X-ray radiation of Si (**b**) for initial state of CFC-8SiC specimen*

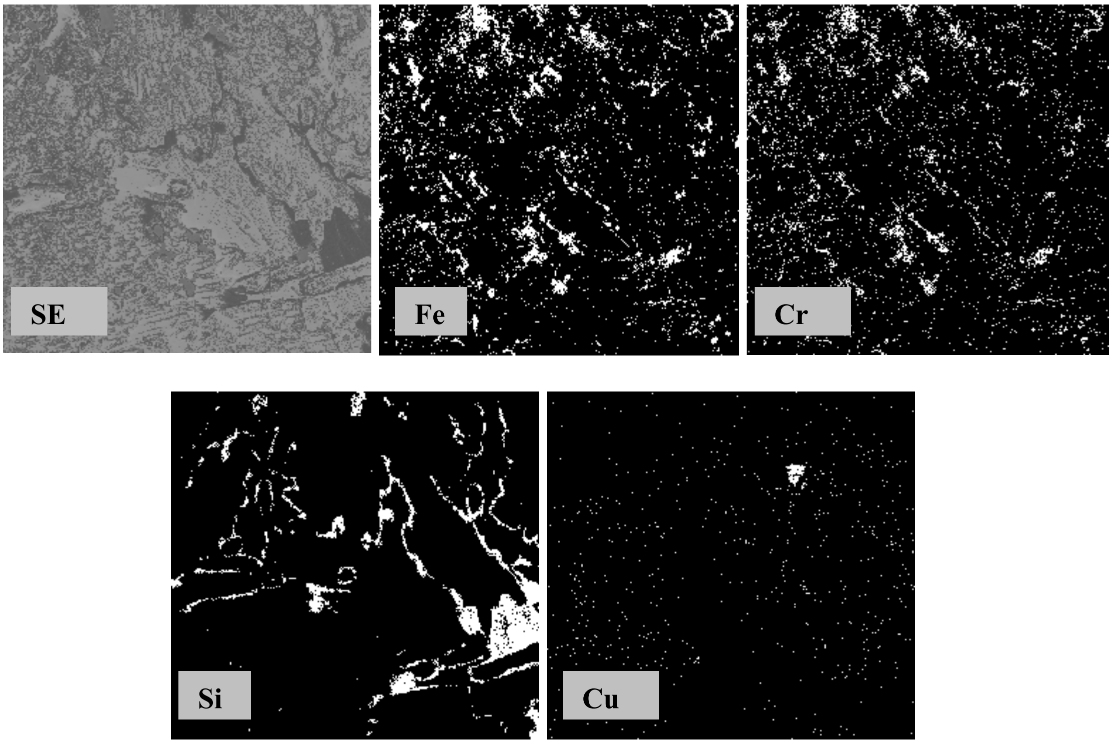


FIG. 10. Second electron image and distribution of characteristic X-ray radiations for Fe, Cr, Si and Cu in CFC-8SiC specimen after irradiation ($q = 10^9$ W/cm^2, 5 pulses)

This result should be taken into account because composites based on CFC are proposed as the most perspective material for application in divertor of Iter. The elements of impurities contained in fusion plasma can be implanted into divertor material and may form new chemical compounds with the material components. It can affect diffusion mobility of deuterium and tritium in divertor material.

4. Conclusion

- It was shown that the main factors for damage of tungsten under high-energy pulses in DPF devices are heat loads resulted in melting of the irradiated surface layers, erosion of materials (mass loss by evaporation and thinning of samples), formation of different types of surface defects and microcracks. Wavelike relief of irradiated surface has advantage for more effective extraction of gases produced inside the material in thermonuclear fusion reactor under plasma irradiation.

- Damage of composite materials of the type of CFC due to erosion is enhanced if carbon fibers displaced normally to irradiated surface.

- Experiment results have confirmed the advantage of Dense Plasma Focus devices for preliminary estimation and test of material behavior in extreme conditions in thermonuclear fusion reactor with inertial plasma confinement.

5. **Acknowledgments** This work was partially supported by the International Atomic Energy Agency (Research Contracts No 14540RO, No 14638RO, No 14526RO) and the "PF-6, Transnational Access Program, MJPF-1000, Contract No RITA 2006-26095.

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