Testing of materials perspective for nuclear fusion reactors with inertial plasma confinement by Plasma Focus and laser devices

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Abstract. A survey of consequences on recent testing of materials perspective for the first-wall components of nuclear fusion chambers with inertial plasma confinement is presented. The main instruments in these irradiation experiments were Dense Plasma Foci facilities of different energy levels and Nd-glass lasers. Results of investigations of physical processes of interaction of powerful plasma jets, streams of fast ions and laser beams with the targets under tests are discussed. Subsequent analytical researches of various characteristics of damageability of dissimilar samples – both surface and bulk of them – are debated.

Keywords: nuclear fusion reactors, Dense Plasma Focus, laser, primary and secondary plasma diagnostics, radiation materials tests.

1. Introduction

Materials designed for positioning of them as the plasma facing components (PFC) on the first wall of the chambers of nuclear fusion reactors (NFR) with inertial plasma confinement (IPC) must withstand the very powerful streams of different kinds of radiation – soft and hard X-rays, neutrons, electrons, but in particular ions. At present time 3 approaches of NFR of this type are elaborated in various laboratories in the world: the so-called “direct-drive” irradiation of a target [1] with power flux density of laser radiation \( P \sim 10^{15} \sim 10^{16} \text{ W/cm}^2 \); the idea of usage of the intermediate element – the cavity called “hohlraum” [2]; and a strategy of a single-beam igniter process [3] where a target preliminary compressed by using \( P \sim 10^{14} \text{ W/cm}^2 \) subsequently fired either by \( P \sim 10^{19} \text{ W/cm}^2 \) or by \( P \sim 10^{16} \text{ W/cm}^2 \) that generates a shock wave with successive burning of the thermonuclear fuel in both cases.

Several laboratories are working under these projects by using lasers of MJ energy level. Among them there are the National Ignition Facility (1.9 MJ, 500 TW, \( \lambda = 0.351 \mu \text{m}, \text{LLNL, U.S.A.} \)), LMG (1.5 MJ, \( \lambda = 0.35 \mu \text{m}, \text{Bordeaux, France} \)), Iskra-6 (300 kJ, 3 ns, \( \lambda = 0.351 \mu \text{m} \)) and UFP-2LM (2.8 MJ, \( \lambda = 0.503 \mu \text{m}, \text{expected in the year 2022, both in Sarov, VNIIEF, R.F.} \)) and OMEGA (27 kJ, \( 10^{15} \text{ W/cm}^2 \), Rochester, U.S.A.). Besides, Z-pinch machines are explored or under construction that use a double-ended hohlraum with a net of exploding wires – Z-machine (20 MJ, 20 MA, 100 ns, Sandia, U.S.A.) with its upgrading versions and Baikal (\( 3 \times 10^{14} \text{ W, 50 MA, 10 MJ in soft X-rays, expected in the year 2020, TRINITY, Moscow region, R.F.} \)).
Numerical modeling of the conditions in NIF facility for a direct-drive scheme and some experiments has shown [1, 4 – 6] that the distribution of the overall 154-MJ fusion energy released at the full-scale experiment will be disseminated among several channels that will irradiate chamber walls of the facility (chamber radius is 6.5 m). Their parameters (individual energy of quasi-particles $E$, efficiency of energy streams $\eta$, power flux density of an irradiation stream on the target’s surface $P$, absorbed dose $D$ and pulse duration $\tau$) expected (and already realized partially) are as follows:

1. Soft X-rays ($\sim 1$-2%): $E_{\text{x}} \leq 10$ keV; $\eta \leq 10\%$; $P \leq 10^8$ W/cm$^2$; $D \sim 1$ J/cm$^2$; $\tau \leq 10$ ns

2. Fast ions ($\sim 30\%$ in three groups):
   - $E_i \leq$ a few MeV; $\eta \sim 30\%$ of fusion origin: $P \sim 10^9$ W/cm$^2$; $D \sim 20$ J/cm$^2$; $\tau \leq 10$ ns
   - $E_i \leq$ a few MeV; $\eta \sim 30\%$ of fusion origin: $P \leq 10^8$ W/cm$^2$; $D \sim 20$ J/cm$^2$; $\tau \leq 0.5 \mu$s
   - $E_i \leq$ 0.5 MeV; $\eta \sim 30\%$ low-energy ions of plasma of debris of targets plus ions accelerated at laser light/plasma interaction: $P \leq 10^8$ W/cm$^2$; $D \leq 20$ J/cm$^2$; $\tau \leq 3$ $\mu$s

3. Neutrons ($\sim 70\%$): $E_n \sim 14$ MeV; $\eta \sim 60-70\%$; $P \leq 5 \times 10^8$ W/cm$^2$; $D \sim 20$–30 J/cm$^2$; $\tau \leq 10$ ns.

As it is seen from these estimations and according to numerical simulations done for the National Ignition Facility (NIF) [1, 4, 6] thermal power for the chamber wall in ions that are counted as the most dangerous factor because of their short projective range in solids and high mass compared with other kinds of emission generated inside the NFR [1 – 4] would be about $P_{\text{NIF}} \leq 10^9$ W/cm$^2$.

Amidst the types of the materials that must be tested for the reliable and efficient use in inertial thermonuclear fusion (ITF) chambers there are the conventional (solid metallic) and liquid metals used as an alternative PFC concept – both to deal with the high power loads at high wall temperatures. These tests have to be provided with the goals to ensure resistibility with respect to heating (powerful short-pulse heat and particle loads), long lifetime (endurance to erosion and material mixing, as well as stable surface morphology maintenance) and safety aspects (fuel retention and removal, material migration, and dust formation). Among them there are the following ones: tungsten [4, 7, 8] and other high refractory materials (Mo, V, etc.), their alloys (see, e.g., [9]) and coatings, high-entropy alloys (such as FeNiMnCr, WTaVCr, VCrTi, VCrTiY, etc. – see, e.g., [10, 11]), reduced-activation ferritic-martensitic (RAFM) steels [12], oxide dispersion strengthened ferritic or ferritic-martensitic steels [13] and other metals reinforced by TiO$_2$, ZnO, Nb$_2$O$_5$, CuO (ODS), various ceramics (carbon fiber composites – CFC, SiC, Al$_2$O$_3$, etc. [14]). At present time nano-structured W and SiC (as a tritium barrier and as an anticorrosion cover), diamond-like carbon (DLC), N$_x$Ti, steels AISI 316L and ASP 30, W with 25% of Re (W25Re) and 1% TiC in W (W-TiC) are under the most intensive tests.

As optical materials in the first wall (windows for laser beams and for diagnostics – i.e. in the final optics) quartz, synthetic crystals of diamond, sapphire, leucosapphire Al$_2$O$_3$, CaF$_2$, MgF$_2$, glass KS-4V and various multilayer nanoparticle armoring are examined.

Pb, eutectics Li17Pb83, Li2BeF4, the alloys of the type, e.g., 01420 Al-Mg-Li [15] for sweating walls of NFR are the candidate wet materials with a thin liquid layer and a thick-liquid protection.

Besides, a number of dissimilar materials prepared for application in constructions of the NFR (Al, Ti, ceramics, etc.) have to be examined under direct irradiations because they may be exposed by energy loads at possible damages or dropping of the PFC inside the chambers of the NFR.

Radiation test experiments can be of two types: to find conditions at which the first-wall materials remain unaffected or, conversely, to investigate different types of their damageability produced in harsher environment. Our experiments are of the second sort. Subsequent examination of the irradiated specimens with contemporary analytical instrumentation has yielded information on the changes in the irradiated materials’ elemental and molecular contents, structure and properties.

2. Irradiation equipment

Fundamental understanding of plasma-wall interaction processes in the mainstream fusion devices requires dedicated R&D activity in plasma simulators. This issue became especially topical after recent advantages in this field – reaching extremely high temperatures in experiments with Z-machine (SNL, USA) and the achievement of fusion fuel gains exceeding unity at the US National Ignition Facility in a scheme of a ‘high-foot’ implosion method. In our experiments on materials’ testing we used Dense
Plasma Focus (DPF) devices as well as lasers on Nd-glass operating in two conditions – in the free-running (FR) mode and in the Q-spoiled (QS) regime. The aims of the works were to contribute to the knowledge-based understanding of the performance and adequacy of the above-mentioned candidate PFC of NFR beyond ignition under short extreme energy and particle loads.

2.1. Dense Plasma Focus facilities
Our DPF installations are “Vikhr’” (5 kJ) and PF-5M (2 kJ) (both of IMET RAS, R.F.), PF-6 (7 kJ) (IPPLM, Poland), PF-12 (6 kJ) (TU, Estonia) and large facility PF-1000U (1 MJ) (IPPLM, Poland) (see figure 1). The first four relatively small devices are capable to work with a repetition rate up to 2 Hz with deuterium and with other working gases. 1-MJ installation may produce shots every 20 min. All these facilities generate bunches of hot plasma (with temperatures $T_{pl} \sim 1$ keV), high-speed plasma jets (speeds $v_J \sim 2 \times 10^5$ m/s) and powerful streams of fast electrons and ions (with energies of these particles $E_{e,i} > 100$ keV extended into the MeV range). The DPF devices are able to produce treatment of specimens in two modes of their operation [16]: with just short (tens of ns) powerful pulses of the above radiations with power flux densities for plasma streams up to $P \sim 10^{14}$ W/m$^2$ and for fast deuterons up to $P \sim 10^{16}$ W/m$^2$, and with relatively long pulse durations (few hundred ns). Both regimes may ensure different temporal, spectral and spatial characteristics of radiations.

2.2. Laser facility
Our standard Nd-glass laser (wavelength $\lambda = 1.06$ μm) named GOS-1001 (see in figure 1 its laser-head) was used [17] also in two types of operation – in a FR mode and in a QS regime – with the overall pulse durations of laser radiation (LR) 0.7 ms and 60 ns correspondingly. The second regime is close to the DPF style of working (and to the regimes realized in NFR with IPC). The free-running mode produces the operating conditions typical for the systems with magnetic plasma confinement (MPC) in their emergency events (e.g. with ELMs).

3. Materials, irradiation conditions and diagnostics

Figure 1. Dense Plasma Focus and laser devices used in testing experiments.
DPF devices are of particular usefulness in the experiments on materials testing for NFR with IPC because these facilities may generate in directed streams namely those particles and with those energies that are observed on the chamber walls of these NFR. Laser pulse in its FR mode may simulate conditions realized in NFR with MPC. But because mechanisms of absorption of laser energy and of particle streams from DPF are different it is also important to compare results of irradiation by these two types of beams with similar characteristics – for a DPF and for a QS regime of laser.

We shall demonstrate here a few results on a number of materials belonging to dissimilar classes that were exploited as targets for irradiation in Dense Plasma Foci and by laser light. Among them we used double-forged W (PLANSEE), tungsten with La doping (used for its better machining), stainless steel Eurofer, ODS and some other types of steels, ceramics CFC, SiC, Al₂O₃, K649 (ZrB₂-31%SiCw-8%Si₃N₄) and K700 (HfB₂-30%SiC), sapphire, etc. Each sample was subjected to 1, 2, 4, 8 and 16 up to 50 consecutive shots. Power flux density of plasma and fast ion streams may be tuned by changing the distance between the top of the pinch and the target under irradiation.

During the DPF devices operation the following parameters were monitored: current derivative by magnetic probes, discharge current by Rogowski coil, neutron and X-ray pulses by photomultiplier tubes with scintillators (PMT+S) (time resolution was ≈ 1.3 ns). Plasma dynamics visualization was provided by 1-ns 4-frame self-luminescence in visual and soft X-ray ranges and 16-frame laser interferometry (second harmonic of Nd-glass laser), absolute neutron yield – by using Ag, In, Y and Be activation counters, etc. Laser energy in a pulse and the pulse duration were measured during irradiation of targets by a laser beam. Laser light intensity can be altered by the focal spot changes.

4. Investigations of physical processes taking place at irradiations of different samples inside the DPF and after the action of laser devices

In figure 2 one may see two laser interferometric pictures and PMT+S pulses of hard X-rays and neutrons taken for the PF-1000U facility operating without a target. By these interferometric pictures (time exposure – 1 ns and time intervals between the frames – 20 or 30 ns) it is possible to measure time duration of hot plasma (HPS) streams of primary plasma in the device. Neutron pulse in a DPF gives information about pulse duration of fast ion streams (FIS). Indeed, because neutrons in a DPF are produced by the beam-target mechanism [16], the neutron yield is ruled by the formula:

\[ Y_n = (n_{pl}N_{i, fast}/4)\sigma_{i, fast}\pi R_p^2 h_p \tau \]

where \( Y_n \) – neutron yield in a shot, \( n_{pl} \) – density of plasma in a pinch, \( N_{i, fast} \) – concentration of fast ions in a pinch which is approximately equal to the overall number of fast ions if one take into account length of the pinch in PF-1000U facility \( h_p \approx 10 \) cm, pinch cross-section area \( \pi R_p^2 \approx 1 \) cm² here, velocity of fast deuterons of energy 100 keV \( v_{i, fast} \approx 3 \times 10^8 \) cm/s, fast deuterons’ pulse duration \( \tau \approx 40 \) ns and the cross-section of the fusion reaction for fast (~ 100 keV) deuterons, respectively.

In figures 3, 4 and 5 one may see 1-ns interferometric images reflecting processes of irradiation of targets manufactured of SiC, stainless steel Eurofer and double-forged tungsten (PLANSEE).
Figure 3. Irradiation of the sample SiC by plasma and fast ion streams with production of secondary plasma propagating from the target to the anode side. Secondary plasma speed \( v_{sp} \approx 1.7 \times 10^7 \text{ cm/s} \).

Figure 4. Interferometric images of irradiation process of stainless steel by plasma and fast ion streams with secondary plasma. Secondary plasma speed \( v_{sp} \approx 1.3 \times 10^7 \text{ cm/s} \).

Figure 5. Irradiation of the sample of tungsten by plasma and fast ion streams with production of secondary plasma. Secondary plasma speed \( v_{sp} \approx 0.56 \times 10^7 \text{ cm/s} \).

These pictures give an opportunity to measure a speed of secondary plasma (SP) created near the surfaces of each of the targets. Note that at the irradiation of light elements (C and Si) this secondary plasma is transparent for the second harmonic of the laser light (\( \lambda = 0.503 \text{ \mu m} \)) whereas for tungsten (see figure 5) it is opaque. Measurements of a velocity of expansion of the SP edge in the direction from the target allow estimating an initial temperature of SP cloud before its expansion [16]. E.g. the temperature of tungsten SP appears to be of the order of 100 eV. It is supported by its opacity for the green laser light used in interferometry.

In figure 6 three time-integrated self-luminescence images (produced in 3 shots) of the pinch (primary plasma – PP, deuterium) and secondary plasma (SP, tungsten) are presented. Besides the luminescence of PP of deuterium (shown by a digit 1) located near the anode (4) on the right-hand side of the pictures a light emission produced by a cloud of SP of W (2) in front of the target is seen –near the target’s holder (5). It has a hemispherical shape, and it is evident that this SP bunch is spreading in the direction opposite to the movement of the PP stream. Moreover, a shock-wave (SW) front (also of a hemispherical shape) (3) is distinctly seen ahead of the SP cloud at a distance from a target of about two times larger compared with the size of the SP bunch.
At first sight these pictures look very strange – the photograph is an integral over time. Why it appeared as an instant print? Such pictures have been observed in our former experiments in soft X-ray range of radiation of the pinch plasma. It was found there by spectroscopic investigations with ns temporal resolution that certain line emission that is higher by intensity compared with bremsstrahlung background and much shorter by time duration (because of fast “burn-out” of the corresponding ionization stage) is able to produce such an effect. It takes place here at pushing of deuterium gas (plasma) by a SP “plunger” spreading from the target surface. This fact testifies a high temperature of secondary plasma produced namely by a powerful stream of fast deuterons [16].

5. Results of irradiations and discussion

In a course of the experiments in radiation material science a high power flux density of plasma ($P \sim 10^{7.10}$ W/cm$^2$) and fast ion streams (FIS) with $P \sim 10^{9.12}$ W/cm$^2$) from DPF were used for irradiation. Also the laser working in a FR mode with $P \sim 10^{5.7}$ W/cm$^2$ and in a QS regime with $P \sim 10^{8.10}$ W/cm$^2$ illuminated various solid state materials. In these experiments the following three unexpected and paradoxical results have been faced:

1) The higher number of shots – the less percentage (concentration) of deuterium was found inside a sample (it was changed from 5% at 1 shot down to less than 0.5% after 8 shots).

2) The higher $P$ of FIS and LR, the less (disproportionally) amount of sample material is evaporated in the conditions of a developed gas-dynamical motion of secondary plasma (see Table 1):

| Device         | Pulse durations (ions/plasma), ns | Power flux density, W/cm$^2$ | Distance from anode, cm | Sample’s material | Number of shots | Mass loss, mg |
|----------------|-----------------------------------|-----------------------------|-------------------------|-------------------|----------------|---------------|
| PF-1000U       | 50/100                            | $10^9$ - $10^{10}$          | 40                      | W                 | 6              | 0.6           |
| PF-1000U       | 50/100                            | $10^{10}$ - $10^{11}$       | 20                      | W                 | 4              | 1.2           |
| PF-1000U       | 50/100                            | $10^{11}$ - $10^{12}$       | 13                      | W                 | 3              | 1.7           |
| PF-1000U       | 50/100                            | $10^{12}$ - $10^{13}$       | 7                       | W                 | 5              | 6             |
| PF-1000U       | 50/100                            | $10^{12}$ - $10^{13}$       | 8                       | Al$_2$O$_3$, CFC, SiC | 6              | 0.5-1.5       |
| PF-1000U       | 50/100                            | $10^{12}$ - $10^{13}$       | 8                       | ZrB$_2$-SiC-Si$_3$N$_4$ | 6              | 1             |
| PF-1000U       | 50/100                            | $10^{12}$ - $10^{13}$       | 8                       | HfB$_2$-SiC       | 6              | 2             |
| Vikhr’         | 20/50                             | $10^9$ - $10^{10}$          | 3.4                     | W                 | 10             | 2             |
| PF-6           | 20/50                             | $10^{11}$ - $10^{12}$       | 3.4                     | W                 | 10             | 4             |
| LR QS          | 80                                | (2-7) $\times 10^9$         | -                       | W                 | 8              | 2             |
| LR FR          | $0.7\times 10^6$                  | $10^5$                      | -                       | W                 | 8              | 0.4           |
| LR FR          | $0.7\times 10^6$                  | $5\times 10^6$              | -                       | W                 | 8              | $\geq 20$     |

It is seen that in the first 4 lines of the table power flux density is increased by 3 orders of magnitude whereas the mass loss is increased by 10 times only.
From this Table 1 one may see also a remarkably low mass removed from ceramics produced at higher flux densities compared with the same parameter with tungsten, but in particular with a laser working in a free-running mode with quite low $P$.

Measurements of the mass loss of tantalum in dependence on the neutron yield of a DPF device (i.e. in comparison with the power flux density of fast ions) gave a picture presented in figure 7.

Results of irradiation of 3 optical materials – sapphire, quartz and topaz – have shown that the best radiation resistivity belongs to the second one (see figure 8, [18]).

SEM images of irradiated stainless steel Eurofer are presented in figure 9. It is seen that a wave-like structure of the surface with initial traces of the micro-cracks nucleation (b) is observed after 1 shot of the PF-6 device. A strongly developed wave-like structure of the surface of the same material (Eurofer) melted with a fracturing pattern and pores (c) become apparent after 5 shots. The characteristic wavelength of the wave-like structure is about a hundred μm.

When a sample is irradiated with a relatively low power flux density with no melting – only an increase of microroughness of its surface is observed – see figure 10 and the paper [19].
Observation of SEM images of cross-sections of W samples (see figure 11) gives an evidence of deeply located cracks oriented in parallel to the surface of the samples.

![Figure 11. SEM photographs of the metallographic sections of W samples with parallel cracks appeared after irradiation by (a) HPS/FIS in the PF-1000U facility at $P_{\text{PF}} \sim 10^{12} \text{ W/cm}^2$ (N = 8) and (b) by LR in QS mode at $P_{\text{LR}} \sim 10^{10} \text{ W/cm}^2$ (N = 8)](image)

Materials on the basis of stainless steel, molybdenum and tungsten mesh (mesh mats) that were soaked with lithium (capillary-porous system – CPS) have also been used in the tests. Figure 12 presents the results of irradiation of CPS by HPS with the power flux density $P \sim 10^6 \text{ W/cm}^2$.

![Figure 12. Surface of W – Li CPS sample after 100 pulses of deuterium plasma with $P = 22 \text{ GW/m}^2$ (a – virgin sample, b and c – two zones after irradiation).](image)

Tungsten wire fragments (1) and oxidation products (2) are visible.

Let’s discuss the above-presented results.

Generally speaking, in various ranges of individual energies of irradiating particles at low their streams’ intensity the following processes will take place: $10^{-2} \ldots 10^1 \text{ eV}$ – thermal activation of materials, $10^1 \ldots 10^3 \text{ eV}$ – desorption, $10^3 \ldots 10^5 \text{ eV}$ – sputtering, $10^5 \ldots 10^7 \text{ eV}$ – implantation.

When the power flux density of the streams of charged particles (with the energy approximately above the value $50 \text{ eV}$) will be increased, the following phenomena will be observed: $10^2 \ldots 10^5 \text{ W/cm}^2$ – sputtering and roughening of the surface, $10^5 \ldots 10^7 \text{ W/cm}^2$ – ablation, cracking, change of phase and elemental content, $10^7 \ldots 10^9 \text{ W/cm}^2$ – same as before plus melting, boiling and evaporation with subsequent very rapid recrystallization, $10^8 \ldots 10^{10} \text{ W/cm}^2$ – same as before plus formation of fully ionized plasma with well-developed gas-dynamical motion, $10^9 \ldots 10^{12} \text{ W/cm}^2$ – the same as before with second and other stages of plasma ionization and beginning of formation of shock-waves inside the irradiated solid-state materials. These pictures will help in explaining of the results obtained.

The first unexpected data concerning a decrease of the deuterium concentration inside the irradiated material with an increase of the number of DPF shots becomes clear if we shall take into account that the previously polished samples prepared for tests will change a morphology of their surface layer acquiring much higher surface area (see figures 8-10) (sometimes nanostructured). The outward gas diffusion of deuterium from samples into the chamber becomes much easier in this case.

The second above-mentioned paradox can be explained taking into consideration physics of evaporation and plasma heating of materials in the regime of the well-developed gas dynamical motion [20]. The energy of HP/FI streams or LR is absorbed by solid target and subsequently is inherited to plasma propagating into space. Then it will be converted into two parts – thermal and kinetic ones divided among them approximately equally [20]. Its kinetic part $E$ is:

$$E \sim M \times T$$

where $M$ – mass of the evaporated material and $T$ is its temperature. From this relation one may see that in dependence on conditions of matter heat process by energy steams we shall either evaporate large masses of matter $M$ with low temperature $T$ (and expansion speed) or low masses with high temperature. From the laws of conservation of energy and of momentum it is easy to draw a conclusion that the
above-mentioned variables are in linear dependence: the higher \( T \) is at irradiation (i.e. the higher power flux density of streams) – the lower \( M \) will be evaporated. This explains the observed disproportionality of the mass loss with an increase of the power flux density of HPS&FIS.

The third unexpected point concerning a remarkably large mass removed in a case of irradiation by a laser working in a FR mode with quite low \( P \approx 5 \times 10^6 \) W/cm\(^2\) may be explained if one takes into account the real regime of its operation. Actually its pulse having the total duration 0.7 ms consists of several hundred individual pulses of 0.6-0.8 \( \mu \)s time durations. Time gap between them is about 3-5 \( \mu \)s. So, at first, its real power flux density is an order of magnitude higher. At second, during the interval between these pulses the evaporated cloud of matter will fly away thus it will not provide any screening for the subsequent pulse (so a well-known detachment effect will not takes place).

In figure 7 the mass loss visible at an absence of neutron yield means that this part of the mass loss belongs to the plasma stream generated in the DPF device – not to FIS. The fact that it is practically constant at all shots signifies that the pinch is very stable in its parameters from shot to shot.

The phenomena of deeply located cracks oriented in parallel to the surface of the samples that are seen in SEM photographs of the metallographic sections of W samples (figure 11) have been subjected to the numerical modelling provided on the base of the work [22]. It was shown that the only explanation for this event is a formation of shock waves (SW) inside the bulk of the material. These shocks have been calculated for two cases – laser irradiation and FIS action in DPF. Results are presented in figure 13 for two materials – Al and W. It is clearly seen that at equal parameters of the irradiation beams the SW amplitudes in the case of FIS are several times higher compared with the laser light. This fact is the consequence of the difference in the regions of absorption of the two beams: in the case of the light from Nd-glass laser the main absorption takes place at the critical density of plasma for its wave-length (\( \lambda = 1.06 \mu m \)) – \( 10^{21} \) cm\(^{-3}\) whereas for the FIS the place where it release its energy is just the surface of the solid-state target – \( 10^{23} \) cm\(^{-3}\). These SW have been observed experimentally in a residual gas at the back side of the metallic foils [16].

![Figure 13](image-url)

**Figure 13.** Numerical simulations of the shock waves generation in two materials – tungsten and aluminum – and by two types of irradiations with equal parameters – laser beams and FI streams.

### 6. Conclusions
1. Main features of degradation of the surface layer of materials of different classes were determined at dissimilar conditions of irradiation by plasma/ion streams in a DPF and by laser radiation in the FR and QS regimes.
2. Chief similarities and differences in damageability obtained in the regimes are fixed – wave-like relief, blisters, craters, porosity, microcracks, and discontinuity flaws, etc. – that are peculiar characteristics for each mode of irradiation and for concrete material.
3. The observed dissimilarities that are particular for each regime of irradiation and for specific material are explained with the help of qualitative analysis, estimations and by numerical modelling.
4. It was found that in the regime of irradiation with the well-developed gas dynamic motion of secondary plasma energy of radiation will be spent preferentially either on large masses removed from the material’s surface or on heating of a small amount of matter to high temperature (and consequently into its fast movement) depending on power flux density and characteristics of pulses of radiation.
5. Parallel use of plasma/fast ion streams from DPF and of laser (in FR and QS modes) irradiations of targets looks perspective for tests of materials designed to withstand extreme thermal loads in the mainstream fusion reactors with inertial and magnetic plasma confinement.
Acknowledgement
This research was provided in the frame of the state task no. № 075-00746-19-00 and was supported by the International Atomic Energy Agency (grants IAEA CRP no. 17167, 19248, 19253, 22745 and 23664).

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