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Potential importance of ultra-deep penetration for operation of IFE power plants

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HIGHLIGHTS

- Ultra-deep penetration of target fragments can be dangerous for inertial fusion energy (IFE) power plants.
- Low-density Xe does not protect the reactor chamber from some target fragments.
- Formation of fragments of hohlraums and/or cones seems to be unavoidable.

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ABSTRACT

Possibility of damage of inertial fusion energy power plants caused by ultra-deep penetration of fragments of targets with hohlraums and/or cones for fast ignition has been investigated in this study. Some issues related to the formation of high-velocity solid and liquid fragments of targets and their deceleration and heating in the reaction chamber filled with low-density Xe gas have been studied. It was found that with a Xe gas mass density of approximately 6 μg/cm^3 and reaction chamber internal radius of 6 m, a liquid spherical gold fragment with a radius of 5–7 μm could reach the chamber wall with a velocity >1 km/s.

1. Introduction

Creation of effective and safe inertial fusion energy (IFE) power plants will be possible only after studying several issues that are important for ignition of microexplosions, target production, as well as operation of drivers and reaction chambers. These issues should be considered at the stage of design optimization of power plants. Analysis of the data available in the literature reveals that ultra-deep penetration (UDP) is one such issue for IFE power plants using targets with hohlraums and/or cones for fast ignition. The term "ultra-deep penetration" is commonly understood as penetration of high-velocity solid particles into the depth L_p of $(100–10^4)\,d$, where d is the diameter or the largest dimension of the nonspherical particle, in a metal target [1–10]. Without UDP, such penetration depth would be much smaller ($L_p/d \leq 10$) [6,7]. According to Ref. [9], UDP occurs when d and particle velocity v_p are in the range of 10–500 μm and 0.5–2.5 km/s, respectively. Values of $d = 2\ \mu$m [4] and $v_p = 300$ m/s [7] and 3 km/s [10] were also mentioned as compatible with UDP. It is important to note that some authors use terms such as "superdeep penetration" [4,6,7,9,11] or "Usherenko effect" [12] to refer to the same effect.

The UDP will damage IFE power plants when unsuccessful ignition of microexplosion transforms some part of the material of hohlraum and/or cone into high-velocity solid and/or liquid objects [13] or, in other words, shrapnel particles. In such situations, UDP can lead to several undesirable consequences. First, the systems for preventing the damage of final optics of IFE power plant with a laser driver are ineffective if they are designed without considering the adverse effects of UDP. Doping and mechanical damage of the reaction chamber wall and equipment for target injection, etc. by the material of hohlraums and/or cones also seem to be possible. Such doping can, for example, deteriorate mechanical properties of the chamber wall material and/or complicate the processing of this material after the end of the power plant operation or after the replacement of the reaction chamber wall [14,15].

UDP is a relatively rare effect [1,2,4–7,9]. Successful ignition of microexplosion and, in some situations, even unsuccessful ones

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will result in a complete ionization and expansion of the target material [15]. However, it should be considered that the operation of IFE power plants will involve ignition of a very large number of microexplosions. For example, Meier et al. have recently described an IFE power plant with a microexplosion repetition rate $R_m = 16.7$ Hz [15]. This rate represents an average number of microexplosions ignited per second. It will be lower than the actual average number of ignition attempts per second because of the failure of some of these attempts [14,16]. The number of microexplosions ignited during 1 year of operation (N_{year}) of the power plant under consideration, with a 2-week break for the replacement of the first wall of the reaction chamber [15], is approximately 5.07×10^8. If some effect is, in principle, possible and the probability of its manifestation per successful ignition of the microexplosion equals p_1, the probability of ignition (p_0^{year}) of N_{year} microexplosions without the manifestation of this effect equals $\exp(-p_1 N_{\text{year}})$ [17]; for example, $p_0^{\text{year}} \approx 0.5$ when $p_1 = 1.37 \times 10^{-9}$. Therefore, it becomes clear that during the IFE power plant operation lasting several months and longer, manifestation of physically important, and in some situations, dangerous effects can occur even at very low values of p_1. Importance of this fact was emphasized by Lev Petrovich Feoktistov, who assumed that in some situations, an implosion could occur without the growth of instabilities and, as a result, the yield from some microexplosions could be extremely high [18] (analysis of this assumption is beyond the scope of this study).

Some problems related to UDP and a possibility of their manifestation in IFE power plants are presented in the following sections.

2. Some reports related to UDP and its supposed mechanism

Experimental data interpreted as the observation of UDP were obtained when bombarding targets with fluxes of solid particles [1–7,10]. The estimated fraction of particles, undergoing UDP, lies in the range of $\leq 3 \times 10^{-3}\%$ [4] to 1% [7,9]. The maximum reliable L_p value, presented in the literature, is approximately 70 mm [5]. This value was obtained in direct experiments on the penetration of cobalt particles with a d value of approximately 10 μm into a steel target [5].

Several models of UDP have been proposed in the literature.

The simplest and, from our viewpoint, the only realistic one, is based on the assumption that this effect is caused by the motion of particles in microcracks [2,9,19]. In experiments described in the literature, microcracks were probably created, or at least widened, by particles which did not undergo UDP or with the participation of such particles [2,9,19]. This explanation is compatible with the experimental data according to which one of the conditions of UDP manifestation is that the density ρ_f of the flux of particles should be sufficiently high, that is, approximately 1 g/cm^3 or higher [6,7,9]. Such high ρ_f seems to correspond to both an increase in the widths of the existing microcracks due to oscillations of the target and/or other effect(s) and the creation of a relatively large number of new microcracks. Situations when only some part of the material of the particle moves in the microcrack also seem to be possible. Models in which UDP was attributed to the motion of particle in the microcrack created by the particle itself were also proposed [20,21].

Several other models have also been proposed [1,3,6,7]. For example, according to the model proposed in Ref. [7], a shock wave generated by particles in the target creates a moving cavity with a lifetime of approximately 1 μs. If a particle that did not take part in the creation of cavity enters it, such a cavity serves as a transport capsule, making UDP of this particle possible [7].

According to Refs. [11,12,22], UDP does not exist at all. Ref. [11] contains a statement that such deep penetration contradicts conservation principles. The alternative explanation of some of the experimental data, interpreted as the manifestation of UDP, has been proposed in Refs. [11,12,22]. This explanation requires additional study and may be valid for some experiments (see also Ref. [19] where experiments in which UDP was not observed are described). However, it should be emphasized that Buravova [11,22] and Adadurov et al. [12] do not discuss the possibility of motion of particles in microcracks, and the statement about the conservation principles [11] is based on equations corresponding to the impact of the single particle and is not supported by analysis of collective effects accompanying the impact of several particles (see also Ref. [4]). It is important to note that the results of the theoretical and experimental studies of the collective effects related to the bombardment of aluminum slabs by steel balls with diameter of 5 mm are presented in Refs. [23,24], respectively. Computer simulation showed that an increase in the penetration depth of the ball could result from the replacement of the target material of the cavity that is created by another ball [24].

3. IFE power plants using targets with hohlraums and/or cones and protection of the reaction chamber walls with low-density gas

The expected scenarios of UDP realization in IFE power plants have several features. A significant fraction of shrapnel particles arising because of the unsuccessful ignition of microexplosions and bombarding final optics or chamber wall, etc. will probably be in a liquid phase, whereas the available experimental data for UDP were obtained for solid particles [1–10]. The data from Ref. [8] and the model explaining UDP as penetration of the particle material in microcracks [2,9,19] allow us to assume that UDP by liquid particles is possible. To the best of our knowledge, UDP was observed only in experiments with the bombardment of metal targets. However, microcracks also exist in dielectric materials [2,25]. Therefore, UDP in dielectric materials, for example, lenses and/or protective glass shields, seems to be possible (see also Ref. [2]). Some of the microcracks providing UDP can be created by thermonuclear neutrons and/or α-particles (see, e.g., Refs. [26,27] and the references therein). The change of mechanical properties of materials of the reaction chamber wall caused by the influence of liquid metal [28] and a relatively slow increase in the surface density of microcracks with time may also be important. It should be emphasized that the aforementioned lower bound of ρ_f [6,7,9] corresponds, to the best of our knowledge, to the experiments with bombardment of targets by a single flux of particles. The model in which UDP results from a motion of particles in the microcracks [2,9,19] is compatible with the assumption of significant UDP probability of a single particle or some part of its material in the target with a sufficiently large surface density of microcracks that arose before the impingement of this particle.

Analysis of deceleration and heating of solid and liquid shrapnel particles in the reaction chamber protected from the influence of microexplosions by low-density Xe gas has been conducted. Such an analysis yields some of the expected parameters of shrapnel particles at their collisions with the reaction chamber wall and the equipment placed inside the chamber, and as such it is useful for estimating a damage that can be caused by these particles because of UDP and/or other effects [29,30].

According to Ref. [15], walls of the reaction chamber of IFE power plant using the indirect-drive targets can be protected by Xe gas with mass density

$$\rho_{\text{Xe}} \approx 6\ \mu\text{g/cm}^3 \qquad (1)$$

The plant has a laser driver [15]. Production of shrapnel particles is considered impossible because of the evaporation of the target by laser beams even when the ignition fails [15]. However, the