SIMULATION OF HIGH POWER DEPOSITION ON TARGET MATERIALS: APPLICATIONS IN MAGNETIC, INERTIAL FUSION, AND HIGH POWER PLASMA LITHOGRAPHY DEVICES

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High power and particle deposition on target materials are encountered in many applications including magnetic and inertial fusion devices, nuclear and high energy physics applications, and laser and discharge produced plasma devices. Surface and structural damage to plasma-facing components due to the frequent loss of plasma confinement remains a serious problem for the Tokamak reactor concept. The deposited plasma energy causes significant surface erosion, possible structural failure, and frequent plasma contamination.

The chamber walls in inertial fusion energy (IFE) reactors are also exposed to harsh conditions following each target implosion. Key issues include intense photon and ion deposition, wall thermal and hydrodynamic evolution, wall erosion and fatigue lifetime, and chamber clearing and evacuation to ensure desirable conditions prior to next target implosion.

Both Laser and Discharge produced plasma are being used as a light source for extreme ultraviolet (EUV) lithography. A key challenge for Discharge Produced Plasma (DPP) and laser produced plasma (LPP) devices is achieving sufficient brightness to support the throughput requirements of High-Volume Manufacturing lithography exposure tools. An integrated model for the description of hydrodynamics and optical processes in a DPP device has been developed, integrated. And benchmarked.

PACS: 52.59.-f, 29.25.-t, 28.50.-K, 24.10.Nz, 21.60.Ka, 32.80.-t

1. MAGNETIC FUSION APPLICATIONS

Interaction of powerful plasma and particle beams (power densities up to hundreds of GW/m^2 and time duration up to tens of ms) with various materials significantly damages exposed target surfaces and nearby components. Investigation of material erosion and damage due to intense energy deposition on target surfaces is essential for many applications: space studies, protection of the earth's surface from colliding asteroids and comets, creation of new sources of radiation, high-energy physics applications, thermonuclear and inertial fusion studies, etc. Experimental and theoretical activities in this field move toward the common goal of achieving a better understanding of the physics phenomena and material properties of various plasma/surface interactions under extreme conditions of high temperature and pressure. An important application of this understanding is in future tokamak fusion devices during plasma interaction with plasma-facing materials (PFMs).

Damage to plasma facing and nearby components as a result of various plasma instabilities that cause loss of plasma confinement remains a major obstacle to a successful tokamak reactor concept. Plasma instabilities can take various forms, such as hard disruptions, which include both thermal and current quench (sometimes producing runaway electrons); edge-localized modes (ELMs), and vertical displacement events (VDEs). The extent of the damage depends on the detailed physics of the disrupting plasma, the physics of plasma/material interactions, and the design configuration of plasma-facing components (PFCs) [1]. Plasma instabilities such as hard disruptions, ELMs, and VDEs will cause both surface and bulk damage to plasma-facing and structural materials. Surface damage includes high erosion losses attributable to surface vaporization, spallation, and melt-layer erosion. Bulk damage includes large temperature increases in structural materials and at the interfaces between surface coatings and structural materials. These large temperature increases can cause high thermal stresses, possible melting and detachment of surface material, and material fatigue and failure. Other bulk effects of some plasma instabilities, particularly those of longer duration, such as VDEs, and those with deeper deposited energy, such as runaway electrons, can cause high heat flux levels at the coolant channels, causing possible burnout of these tubes [2]. In addition to these effects, the transport and redeposition of the eroded surface materials to various locations on plasma facing and nearby components are a major concern for plasma contamination, safety (dust inventory hazard), and successful and prolonged plasma operation after instability events [3]. Figure 1 is a schematic illustration of the various interaction zones and physics currently included in the High Energy Interaction with General Heterogeneous Target Systems (HEIGHTS) simulation package in a self-consistent and integrated way during plasma instability events.

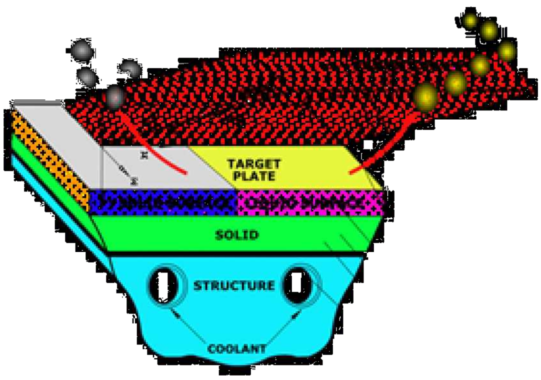

Fig. 1. Schematic illustration of various interaction zones and physics involved during plasma instabilities [1]

Several key factors can significantly influence the overall response and erosion lifetime of a PFC as a result of the intense energy that is deposited during these plasma instabilities. These factors are (a) characteristics of particle-energy flow (i.e., particle type, kinetic energy, energy content, deposition time, and location) from the scrape-off-layer (SOL) to the divertor plate; (b) characteristics of the vapor cloud that develops from the initial phase of energy deposition on target materials and its turbulent hydrodynamics; (c) generated-photon radiation and transport in the vapor cloud and nearby regions; and (d) characteristics of plasma/solid/melt-layer/debris interactions.

The HEIGHTS simulation package has been developed to study in detail the various effects of sudden high-energy deposition of various sources on target materials [4]. The developed package consists of several integrated models that follow the beginning of a plasma disruption at the SOL up to the transport of the eroded debris and splashed target materials as a result of the deposited energy. One model in the package, the SOLAS code, explains the plasma behavior in the SOL during a disruption and predicts the plasma parameters and conditions at the divertor plate.

To evaluate the magnitude of various damage mechanisms to plasma facing and nearby components caused by plasma instabilities, we have developed full multidimensional comprehensive radiation magnetohydrodynamic (MHD) models that use advanced numerical techniques such as particle-in-cell (PIC), forward-reverse, and Ray Tracing methods [4]. These models, which use such advanced numerical methods, are needed for a realistic analysis of disruption conditions and overall consequences. Detailed physical models of plasma/solid-liquid/vapor interaction in a strong oblique magnetic field have also been developed in a fully self-consistent multidimensional model that is coupled with radiation MHD models.

Factors that influence the lifetime of PFCs such as loss of vapor-cloud confinement and vapor removal due to MHD instabilities, damage to nearby components from intense vapor radiation, melt splashing, and brittle destruction/explosive erosion of target materials, can also be modeled in detail [1]. The HEIGHTS package being used for reactor design estimates is validated against well-diagnosed experiments in disruption simulation facilities [5]. A major part of the current work focuses on modeling the behavior and erosion of a metallic surface with a liquid layer, subject to various internal and external forces during the energy deposition phase, as on the explosive erosion, and on the characteristics of brittle-destruction erosion of carbon-based materials (CBMs). Although in general, good agreement is found for many of the cases studied, discrepancies still exist and must to be resolved.

Accurate prediction of mass losses requires full descriptions of evolving media above the target surface that consist of a mixture of vapor and macroscopic particles (MPs) moving toward the disrupting plasma. Photon radiation from the upper hot region of the vapor will then be absorbed by both divertor surface and the surface of the ejected MPs. This leads to further surface vaporization of divertor and MP surfaces. In such a mixture, additional screening of the target surface by the MP cloud can occur. This could lead to a significantly reduced power flux to the surface due to "droplet shielding," which is analogous to the vapor shielding effect [1]. In a well-confined vapor cloud, the flight lifetime of MPs in the vapor is short, and complete burning of the emitted MPs occurs. This droplet shielding effect can lead to further reduction of the total erosion loss.

To correctly predict macroscopic erosion, a four-moving-boundaries problem is solved in HEIGHTS. The front of the vapor cloud is one moving boundary, determined by solving vapor hydrodynamic equations. The second moving boundary, due to surface vaporization of the target, is calculated from target thermodynamics. A third moving boundary, behind the surface vaporization front, is due to the melt-splashing front. Finally, the fourth moving boundary is at the liquid/solid interface; it further determines the new thickness of the melt layer. The SPLASH code (part of the HEIGHTS package) calculates mass losses by using the splashing-wave concept as a result of each erosion-causing mechanism [1]. Thus, total erosion is calculated from the sum of all possible erosion mechanisms. An overall prediction of erosion lifetime of PFCs would then include surface vaporization, macroscopic erosion from liquid-metal splashing and brittle destruction of CBMs, and erosion damage to nearby components from intense vapor radiation and deposition.

In future tokamak devices, ≈10…200 MJ·m^{-2} will be deposited on the divertor plates during the disruption thermal quench, a time of the order of 0.1…10 ms. These corresponds to a heat fluxes >10 GW·m^{-2}. Figure 2 shows a typical time evolution of a tungsten surface temperature, melt-layer thickness, and vaporization losses during a disruption for an incident plasma energy of 100 MJ/m^2 deposited in 1 ms, as predicted by the HEIGHTS package [1]. An initial magnetic field strength of 5 T with an incident angle of 2-6º is used in these calculations. The sharp initial rise in surface temperature is due to the direct energy deposition of incident plasma particles at the material's surface. The subsequent decrease in the surface temperature was caused by the reduction in absorbed heat flux due to vapor shielding and conduction of heat into the material. The subsequent behavior is mainly determined by the energy flux from the emitted photon radiation in the vapor cloud, as discussed above, and by vapor-electron heat conduction. The overall material erosion from vaporization is reduced by about two orders of magnitude due to the vapor shielding effect. However, melt layer splashing and erosion can be significant [1].

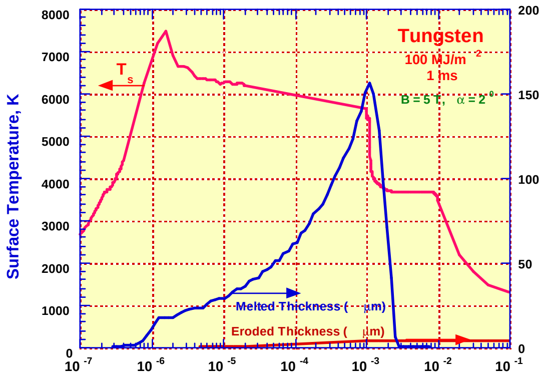

Fig.2. Time evolution of tungsten surface temperature, melting thickness and vaporization losses during a disruption

2. INERTIAL FUSION APPLICATIONS

In inertial fusion systems, the power to the first wall resulting from X-rays, neutrons, energetic particles, and photon radiation is high enough to cause damage and dynamically affect the ability to reestablish chamber conditions prior to the next target implosion. In the case of a dry-wall protection scheme, the resulting target debris will interact and affect the surface wall materials in different ways. This can result in the emission of atomic (vaporization) and macroscopic particles (i.e., liquid droplets or carbon flakes), thereby limiting the lifetime of the wall. The mass loss in the form of macroscopic particles can be much larger than mass loss due to surface vaporization and has not been properly considered in past studies as part of the overall cavity response and re-establishment. This could significantly alter cavity dynamics and power requirements.

Figure 3 shows a schematic illustration of IFE cavity chamber and debris-wall interaction processes during the micro-explosion. The overall objective of this work is to create a fully integrated model within the frame of HEIGHTS software package to study chamber dynamic behavior after target implosion. This model and package, HEIGHTS-IFE, includes cavity gas hydrodynamics, the particle/radiation interaction, the effects of various heat sources (e.g., direct particle and debris deposition, gas conduction, convection, and photon radiation), chamber wall response and lifetime, and the cavity clearing. The model emphasizes the relatively long-time phenomena following the target implosion up to the chamber clearing in preparation for the next target injection. It takes into account both micro- and macroscopic particles (mechanisms of generation, dynamics, vaporization, condensation, and deposition due to various heat sources: direct laser/particle beam, debris and target conduction, convection, and radiation). These processes are detrimental and of significant importance to the success of IFE reactors [6,7].

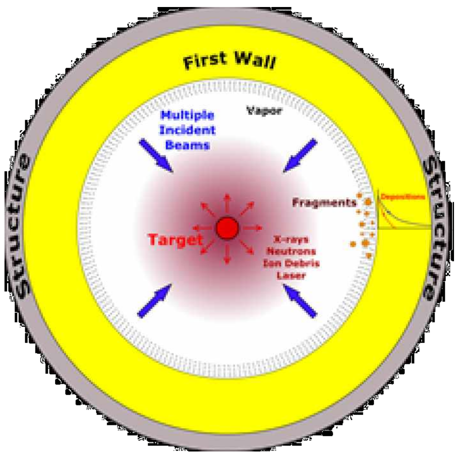

Fig. 3. Schematic illustration of IFE cavity chamber and debris-wall interaction

The hydrodynamic response of gas-filled cavities and photon radiation transport of the deposited energy have also been calculated in detail by means of new and advanced numerical techniques [8]. In addition, fragmentation models of liquid jets as a result of the deposited energy have been developed, and the impact on chamber clearing dynamics has been evaluated [9]. As an example, the surface temperature of the tungsten wall material is presented in Fig. 4. This calculation is for a bare-wall concept with no protection and shows the time evolution of the wall thermal response in both time and depth due to the sequence of different incident species [10]. Gas filled cavity does reduce the wall temperature depending on the amount of gas pressure. However, the gas does not cool down to acceptable temperature prior to the next target implosion. Thin liquid-metal layers also protect the structure from significant erosion but the concern is to re-establish the cavity chamber conditions prior to the next target implosion.

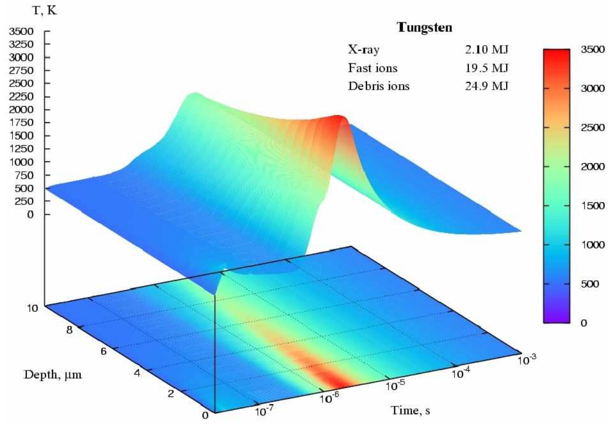

Fig. 4. Temperature rise due to laser, X-ray, and ion depositions [10]

3. ADVANCED LITHOGRAPHY APPLICATIONS

Both Laser and Discharge produced plasma are being used as a light source for extreme ultraviolet (EUV) lithography. A key challenge for Discharge Produced Plasma (DPP) devices is achieving sufficient brightness to support the throughput requirements of High-Volume Manufacturing lithography exposure tools. One method for improving source brightness is to simulate the source environment in order to optimize the EUV output. An integrated model for the description of hydrodynamics and optical processes in a DPP device has been developed and integrated into the HEIGHTS–EUV computer simulation package. Model development consisted of three main tasks: plasma evolution and MHD processes; detailed photon radiation transport, and physics of plasma/electrode interactions in DPP devices. Plasma flows have multidimensional character in pinch systems. Advanced numerical methods for the description of magnetic compression and diffusion in a cylindrical geometry are used in the HEIGHTS package. The package can also study detailed hydrodynamic and radiation processes in various laser produced plasma (LPP) devices as a function of laser energy, wavelength, and dimensions to optimize brightness throughput. For the opacity calculations several models have been developed and implemented. Radiation transport of both continuum and lines is taken into account with detailed spectral profiles in the EUV region. A multi-group approximation of opacities with detail resolution of several thousand strong spectral lines is used. Radiation transport is solved using two different methods, i.e., by direct integration of the transport equation and by 3-D Monte Carlo techniques. Discharges using Xenon and Tin gasses are simulated and compared. Response of electrode materials in DPP devices to plasma particles and radiation interactions are also studied. The HEIGHTS-EUV package can be used to optimize brightness throughput in both DPP and LPP devices.

The results of simulation a DPP device depend on the detailed physics of the discharge, the geometrical design features of the device, the electric circuit design, the initial parameters in the chamber, and the current profile. The pinch size, duration, and place are the most critical parameters for the collection of the radiation output and the common trend is to obtain the smaller and brighter pinch. The discharge dynamics of a typical xenon-driven dense plasma focus device is shown in Fig. 5. Soon after the current circuit is triggered, the formation of the pinch starts by the plasma arcs moving toward the axis of symmetry of the device (a and b in Fig. 5). Once the arcs have touched each other, the pinch is formed (c), which is followed by the pinch decay (d).

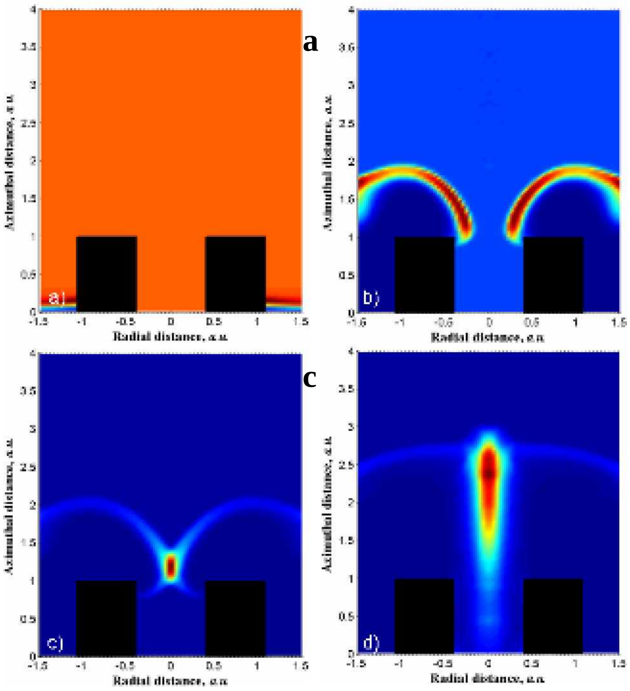

Fig. 5. Dynamics of a typical dense plasma focus pinch discharge: (a) initiation, (b) pinch formation, (c) pinch time, and (d) pinch decay

An ideal source of the EUV in-band radiation is a small sufficiently dense spherical object heated to a specified temperature. The emissivity of plasma within a certain wavelength range is material dependent and identification of the most appropriate material composition for the maximal in-band radiation constitutes the first part of a challenging problem. The major difficulty of the task is the emission of radiation within a wide range of wavelengths from plasmas. This difficulty is dictated by EUVL technology applications operating in a narrow range, which consists, for candidate EUV radiators; lithium, xenon, or tin materials around 1-3 percent of the total radiation emission spectrum. This places a heavy burden in the accuracy and fidelity of the simulation. We have carried out the simulation of a tin planar target subject to a laser pulse with typical EUV lithography parameters, energy pulse and duration. The simulation result of plasma parameters shows that the in-band emitting region is a very thin layer between the regions with high temperature and low density, and low temperature and high density. Increasing the thickness of the in-band emitting region is the second part of the task toward the larger conversion efficiency of a laser-produced plasma configuration. We have verified by our simulations that this thickness is material-dependent. For example, lithium is a very active EUV emitter; however, produces a very thin layer. Laser radiation is actively absorbed by the lithium target surface and quickly overheats the material, because the lithium atomic structure has only three electrons. Once the lithium material is fully ionized and heated to around 1 eV, it becomes transparent to the remaining laser

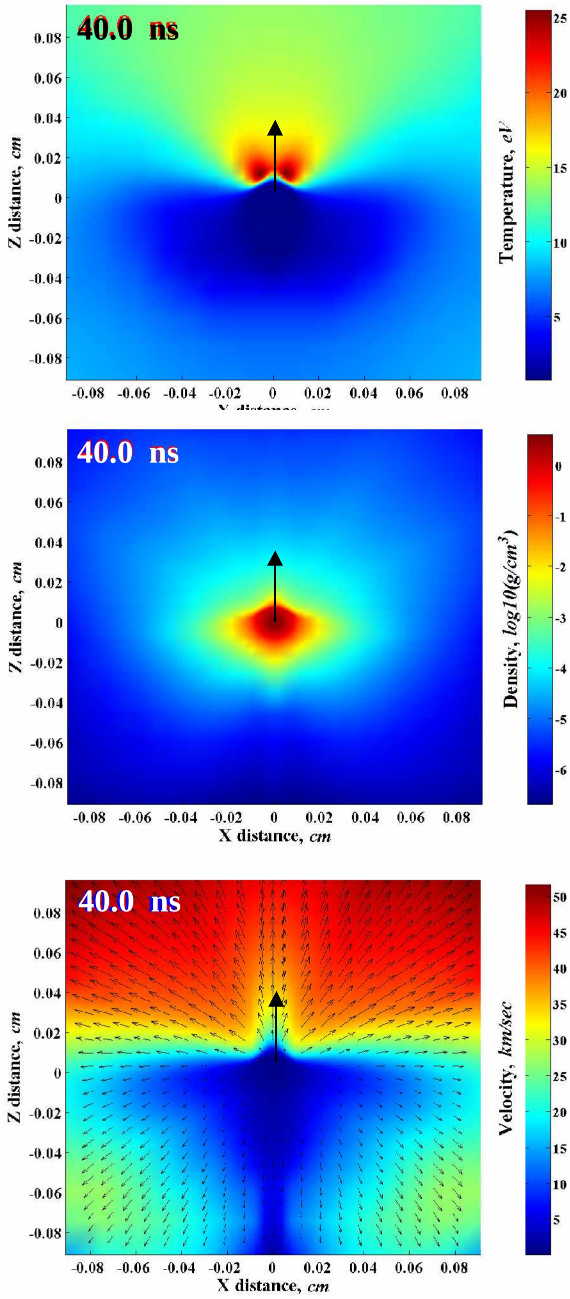

Fig. 6. Temperature, density and velocity of the tin plasma formed from three-laser beam assembly on a tin droplet. Three lasers case: energy of laser pulse 45 mJ, wavelength 1064 nm, θ = 30°

energy. By choosing an axial angle θ between the three laser beams, the laser-formed plasma jet would be effectively confined along the radial direction. To verify our suggestion, we have provided full 3-D simulation of the three-beam LPP assembly subject to a tin droplet target. The total energy pulse was distributed equally between the lasers fired simultaneously on the target. Results of the simulation are presented in Fig. 6. The conversion efficiency of the new device was increased to 11%, which is a significant increase for EUV applications, considering that relatively minor increases (50…70% more than CE ~ 2.5%) are obtained with great effort. Additional studies are required to optimize the assembly accounting for various energy distributions, non-equal timing of the device, mutual locations of the laser beams, various target designs and many other issues.

CONCLUSIONS

The experience gained from the use of HEIGHTS package, which contains unique models and physics for magnetic fusion energy, was applied to simulate the dynamics of chamber behavior in inertial fusion reactors (HEIGHTS-IFE) and the response of EUV lithography devices (HEIGHTS-EUV). Various aspects of the HEIGHTS models have been benchmarked and tested against worldwide simulation devices and tokamak reactors in Japan, Europe, Russia, and the US.

Besides magnetic fusion research, the HEIGHTS package has been used and is currently being applied to space program applications, high-energy physics program (muon collider and neutrino factory projects), nuclear physics program (RIA project) and medical (isotope production and arc injury), and other defense applications.

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МОДЕЛИРОВАНИЕ ВОЗДЕЙСТВИЯ ВЫСОКИХ МОЩНОСТЕЙ НА МАТЕРИАЛЫ МИШЕНЕЙ: ПРИМЕНЕНИЕ В МАГНИТНОМ, ИНЕРЦИАЛЬНОМ СИНТЕЗЕ И МОЩНЫХ ЛИТОГРАФИЧЕСКИХ ПЛАЗМЕННЫХ УСТРОЙСТВАХ

А. Хассанейн

Воздействие на материалы больших потоков мощности и частиц встречается во многих приложениях, включая термоядерные установки с магнитным удержанием и инерциального синтеза, в ядерной физике и физике высоких энергий, в устройствах с плазмой, образуемой разрядами или с помощью лазеров. Структурные и поверхностные повреждения обращенных к плазме компонентов в результате повторяющихся случаев потерь удержания остаются серьезной проблемой в концепции реактора-токамака. Плазменное воздействие может вызывать сильную эрозию поверхности, структурные повреждения, и загрязнение плазмы в объеме удержания.

Стенки камеры в энергетических реакторах на основе инерциального синтеза также будут находиться в суровых условиях при каждом взрыве мишени. Важным здесь являются интенсивные потоки фотонов и ионов, тепловое и гидродинамическое воздействие, эрозия стенок и усталостное разрушение, очистка камеры и обеспечение необходимых условий перед взрывом следующей мишени.

Лазерная или разрядная плазма используется в качестве источника вакуумного ультрафиолета (ВУФ) для литографии. Определяющим в установках с разрядной и лазерной плазмой является достижение достаточной яркости для обеспечения высокой производительности при массовом производстве оборудования для литографии. Для описания гидродинамики и оптических процессов в разрядной плазме была разработана и испытана комплексная модель, обсуждаемая в настоящей работе.

МОДЕЛЮВАННЯ ВПЛИВУ ВИСОКИХ ПОТУЖНОСТЕЙ НА МАТЕРІАЛИ МІШЕНЕЙ: ЗАСТОСУВАННЯ В МАГНІТНОМУ, ІНЕРЦІАЛЬНОМУ СИНТЕЗІ І МОГУТНІХ ЛІТОГРАФІЧНИХ ПЛАЗМОВИХ ПРИСТРОЯХ

А. Хассанейн

Вплив на матеріали великих потоків потужності і часток зустрічається в багатьох застосуваннях, включаючи термоядерні установки з магнітним утриманням і інерціального синтезу, у ядерній фізиці і фізиці високих енергій, у пристроях із плазмою, утвореної розрядами або за допомогою лазерів. Структурні і поверхневі ушкодження звернених до плазми компонентів у результаті повторюваних випадків втрат утримання залишаються серйозною проблемою в концепції реактора-токамака. Плазмовий вплив може викликати сильну ерозію поверхні, структурні пошкодження, і забруднення плазми в області утримання.

Стінки камери в енергетичних реакторах на основі інерціального синтезу також будуть знаходитися в суворих умовах при кожному вибуху мішені. Важливим тут є інтенсивні потоки фотонів і іонів, тепловий і гідродинамічний вплив, ерозія стінок і руйнування від утомленності, очищення камери і забезпечення необхідних умов перед вибухом наступної мішені.

Лазерна або розрядна плазма використовується як джерело вакуумного ультрафіолету (ВУФ) для літографії. Визначальним в установках з розрядною і лазерною плазмою є досягнення достатньої яскравості для забезпечення високої продуктивності при масовому виробництві обладнання для літографії. Для опису гідродинаміки й оптичних процесів у розрядній плазмі була розроблена і випробувана комплексна модель, обговорювана в даній роботі.