Integrated Models for Plasma/Material Interaction during Loss of Plasma Confinement

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Abstract

A comprehensive computer package, High Energy Interaction with General Heterogeneous Target Systems (**HEIGHTS**), has been developed to evaluate the damage incurred on plasma-facing materials during loss of plasma confinement. The HEIGHTS package consists of several integrated computer models that follow the start of a plasma disruption at the scrape-off layer (SOL) through the transport of the eroded debris and splashed target materials to nearby locations as a result of the energy deposited. The package includes new models to study turbulent plasma behavior in the SOL and predicts the plasma parameters and conditions at the divertor plate. Full two-dimensional comprehensive radiation magnetohydrodynamic models are coupled with target thermodynamics and liquid hydrodynamics to evaluate the integrated response of plasma-facing materials. A brief description of the HEIGHTS package and its capabilities are given in this work with emphasis on turbulent plasma behavior in the SOL during disruptions.

I. Brief description of HEIGHTS package

Three key factors significantly influence the overall response and erosion of plasma-facing components (PFCs) as a result of the intense deposited energy during plasma instabilities. These are (a) the characteristics of particle-energy flow (i.e., particle type, kinetic energy, energy content, deposition time, and location) from the SOL to the divertor plate, (b) the characteristics of the vapor cloud that develop from the initial phase of energy deposition on target materials and its turbulent hydrodynamics, and (c) the generated-photon radiation and its transport in the vapor-cloud and nearby regions. The HEIGHTS package consists of several integrated models that describe and follow the start of a plasma disruption at the SOL through the transport of the eroded debris and splashed target materials, after the end of a disruption, to nearby locations as a result of the intense energy deposited.

The characteristics of particle-energy flow from the core plasma to the SOL during plasma instability events are studied with the recently developed **SOLAS** model, in which an analytical solution is derived for plasma particle distribution functions in SOL by using a modified form of the Fokker-Planck equation [1]. The dynamics of target thermal evolution, surface erosion due to vaporization, vapor-cloud formation and shielding effects, magnetohydrodynamic (MHD) expansion, vapor turbulent instabilities, and loss of confinement are studied with the comprehensive **A*THERMAL-S** code [2]. Most of the incident plasma kinetic energy during a disruption, however, will quickly be transformed into photon radiation if the vapor cloud is to be well confined by the magnetic field. The resulting photon radiation from the continuous plasma heating of the vapor cloud and the transport of the emitted radiation are very important and complicated problems. Vapor radiation in a closed divertor design can cause significant erosion of nearby components. For such analysis, the **PhD** and the **SUPERATOM** codes [3] are used; each is coupled to the A*THERMAL-S code. The PhD code calculates detailed deposition of the emitted photon radiation from the vapor cloud to nearby components. The SUPERATOM code calculates the atomic physics data of different target materials needed for calculation of the resulting radiation.

The behavior and erosion of the free metallic surface of a liquid layer subject to various internal and external forces during the disruption are studied with the **SPLASH** code [4]. In addition, the SPLASH code calculates the explosive erosion and the characteristics of brittle destruction erosion of carbon-based materials (CBMs). Macroscopic erosion of metallic and carbon-based materials can significantly exceed conventional erosion from surface vaporization by orders of magnitude. The redeposition of the eroded debris and splattered materials are analyzed with the **DRDEP** code [3]. Redeposited debris is of major concern for plasma contamination, for safety (dust inventory hazard), and for successful and prolonged plasma operations following plasma instability events. Tritium behavior and containment in the generated dust and eroded debris of plasma-facing materials (PFMs), as a result of various plasma instabilities, are being analyzed and evaluated with the **TRICS** and **TRAP** codes. Detailed models and initial results of these codes are described elsewhere and will not be discussed here [5].

The emphasis in this work is devoted to understanding turbulent plasma behavior in the SOL during a disruption. The analytical SOLAS code has been developed to predict the disrupting plasma parameters at the divertor plate. These parameters are then used as an input to the remaining HEIGHTS package to determine the overall response and lifetime of PFCs to plasma instabilities.

III. Plasma behavior in scrape-off layer (SOLAS code)

During various plasma instability events, the loss of confinement will cause the majority of the core particle flux to arrive at the SOL with a relatively high temperature $T \approx T_o$, where T_o is the core plasma temperature ($T_o \approx$ 10-20 keV) prior to a disruption. This is in contrast to the normal operation scenario in which the escaping particles from the core plasma to a collisional SOL have a relatively lower temperature, $T < 1$ keV. Because of the high temperature of the escaping particles during plasma instability events, the SOL plasma becomes collisionless and requires different treatment than that during normal operation.

In the SOLAS code, the electrons in the SOL are considered to be composed of three different populations based on their origin. Hot electrons arriving from the tokamak core

plasma will have two different destinies according to their energy E and momentum $\vec{P}$. Electrons with parallel momentum, $P_{II} = mV_{II}$, and energy $E_{II} = P_{II}^2 / 2m$ exceeding the stopping potential, $|\phi|$, i.e., $E_{II} > |\phi|$, will escape the SOL in shorter time $\tau_{II}^{hot} \approx L / V_{Te}$ which is $\sqrt{M/m}$ less than ions escaping time $\tau_{II}^{i} \approx L / V_{Ti}$. The remaining electrons with $E_{II} < |\phi|$ will be trapped in the established electrostatic potential. The characteristic lifetime of those trapped electrons is determined from the diffusion time $\tau_e^t \propto \phi_0^{3/2}$ in momentum space. The third electron population is the "cold" secondary electrons that arrive from the divertor plates or vapor plasma near the divertor plates in order to keep the net current to these plates equal to zero, i.e., $j_e^{hot} + j_e^{cold} + j_e^{trap} + j_i = 0$.
The residence time of the cold electrons $\tau_e^{cold} \approx L / \sqrt{2e\phi_0 / m}$ is similar to τ_{II}^{hot} because $\phi_0 \approx T_0$. The total flux of the cold electrons is $S_e^{cold} = \gamma\left(S_e^{hot} + S_e^{trap}\right)$, where γ is the wall emissivity of the secondary electrons.

The condition for quasineutrality of the SOL plasma is given by $n_i = n_e^{cold} + n_e^{hot} + n_e^{trap}$. The ion positive charge is neutralized mainly by the negative charge of the trapped electrons because densities of the escaping and cold electrons are very low. Therefore, the main problem is to find the trapped electron density, n_e^{trap}. The stationary kinetic equation for the trapped electron distribution function, F, is given from the solution of the Fokker-Planck equation [1]. The solution is found to have the form

$$F = n_e^{trap} \cdot \tfrac{2}{\sqrt{2\pi}} C_q \cdot e^{-P^2/2} \cdot \left[1 - aP + a\tfrac{P^3}{3} + ae^{P^2/2}\Phi(P)\right], \qquad (1)$$

where $\Phi(P)$ is the probability integral, and C_q is defined from the normalization condition: $n_e^{trap} = n_i$. The value of potential $\phi_0 = P^{*2}/2$ can be found from the boundary condition $F(P^*) = 0$. The numerical solution has the following two asymptotes:

$$a \Rightarrow \infty; \quad P^* \Rightarrow \left(\tfrac{3 \cdot 5}{a}\right)^{1/5}; \ \phi_0 \Rightarrow \tfrac{1}{2}\left(\tfrac{3 \cdot 5}{a}\right)^{2/5} \text{ and } a \Rightarrow 0; \ P^* \Rightarrow \sqrt{2\ln\left(\tfrac{2}{\sqrt{2\pi}}\tfrac{1}{a}\right)}; \ \phi_0 \Rightarrow \ln\left(\tfrac{2}{\sqrt{2\pi}}\tfrac{1}{a}\right). \qquad (2)$$

The parameter, a, defined from C_q is also calculated numerically. Therefore, the wall potential, ϕ_0, depends on tokamak dimensions, i.e., major radius, R, and minor radius, r, depends on core plasma density and temperature via electron collision frequency, ν_0, and electron thermal velocity, V_{Te}, and particle loss time, τ_p.

For future tokamak devices with R = 6 m, r = 1 m, $T_0 = 20$ keV, $n_0 = 10^{14}$ cm^{-3}, $\tau_p = \tau_d \approx 1$ ms, the parameter a $\approx$ 6.5 is large enough to use the asymptotes $a \Rightarrow \infty$; therefore $P^* = 1.1$, $\phi_0 = 0.65$. Therefore, the trapped electron density $n_e^{trap} = 3\ n_0$ and the mean temperature, T_{sol}, (energy) is $T_{sol} = \phi_0 T_0 = 13$ keV. The escaping electrons density is found to be similar to the cold electron density: $n_{hot} \approx n_{cold} \approx 10^{-2}\ n_0$. The calculated different electron heat fluxes, as well as the ion heat flux, are then used by the rest of the HEIGHTS simulation package to evaluate the response and lifetime of plasma-facing components in regard to plasma instabilities.

IV. SUMMARY

A comprehensive computer package known as the High Energy Interaction with General Heterogeneous Target Systems (**HEIGHTS**) has been developed and consists of several integrated computer models that follow the beginning of a plasma disruption at the scrape-off layer (SOL) through the transport of the eroded debris and splashed target materials to nearby locations as a result of the intense deposited energy. The package can now be used to study turbulent plasma behavior in the SOL and predicts the plasma parameters and conditions at the divertor plate. The analytical SOLAS code for the collisionless SOL during a disruption was developed to determine the energy fluxes and spectra incident on the divertor plate. The main results can be summarized as follows: (a) the SOL acts as an electrostatic trap. The electron distribution function includes three different populations (hot electrons beams, cold electron beams, and trapped electrons); (b) ion charge is neutralized mainly by trapped electrons; and (c) the sheath potential depends on device geometry and on core plasma parameters. Results from the SOLAS code make it possible to understand the roles of the various physical processes involved and the effect of device geometry on incident plasma parameters during disruptions. More detailed considerations that use numerical methods are required for better accuracy. Such a study is currently underway. The results of the SOLAS code are used in the A*THERMAL-S code to predict target debris hydrodynamic evolution and photon radiation transport. The PhD code calculates net radiation power to the target surface and nearby components. The SPLASH code then predicts target lifetime due to macroscopic erosion. Finally, the DRDEP code can then calculate redeposition of eroded and splashed material.

Acknowledgments

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References

[1] A. Hassanein and I. Konkashbaev, "An analytical model for a collisionless scrape-off-layer plasma during disruptions and enhanced phase of normal operations," submitted to Physics of Plasma, June 1998.

[2] A. Hassanein, Fusion Technol. Vol. 30 (1996) 713.

[3] A. Hassanein and I. Konkashbaev, Plasma Devices and Operations, Vol. 5 (1998) 297.

[4] A. Hassanein and I. Konkashbaev, J. Nucl. Mater 233-237 (1996) 713.

[5] A. Hassanein, B. Wiechers, and I. Konkashbaev, "Tritium Behavior in Eroded Dust and Debris of Plasma-Facing Materials," presented at 8th Int. Conf. on Fusion Reactor Materials (ICFRM-8), Oct. 26-31, 1997, Sendai, Japan, to be published in J. Nucl. Material.