Journal of Nuclear Materials 390–391 (2009) 777–780

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Integrated simulation of plasma surface interaction during edge localized modes and disruptions: Self-consistent approach

A. Hassanein *, T. Sizyuk, I. Konkashbaev

Purdue University, 400 Central Dr., West Lafayette, IN 47907, USA

A B S T R A C T

Edge-localized modes (ELMs) and disruptions remain a major concern to divertor plasma-facing components (PFCs) during normal and abnormal operation of future tokamaks. Of particular concern are the pulses of energy and particles that are transported during ELMs to the divertor surface. ELMs, therefore, can result in excessive divertor erosion and plasma contamination. A two-fluid model is enhanced to include detail atomic physics data for tungsten, lithium, and neon in multidimensional geometry to integrate core, SOL parameters, and divertor surface evolution (melting, vaporization, vapor cloud dynamics, etc.) using the HEIGHTS numerical simulation package. ELM mitigation using liquid Li surface and neon gas puffing are also simulated. Initial results indicate that a thin layer of Li (<1 mm) can fully protect the divertor surface from giant ELMs. Significant amount of neon gas puff (nL > 10^{17} cm^{-2}) is needed to prevent tungsten surface from melting during giant ELMs. Vapor impurity diffusion through the private flux region can be major source of plasma contamination during ELMs and could terminate the plasma in a disruption.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Plasma-chamber performance in current and future fusion devices is probably the most critical issue in the development of fusion power. The plasma-facing components (PFCs), e.g., wall, divertor, and limiter surfaces of a tokamak are subjected to intense particle and heat loads during major disruptions, edge-localized modes (ELMs), and vertical displacement events (VDEs) [1–3] and must maintain a clean and stable surface environment between the core/edge plasma. The ultimate objectives of plasma material interaction simulations are to establish comprehensive understanding of the issues that affect plasma chamber performance in future fusion systems and to develop innovative concepts and conditions for best performance and successful operation of future fusion devices.

Edge-localized modes (ELMs) are currently the focus of great attention because of the impact of the high power and particle deposition on the divertor design, plasma operation, and lifetime. During ELMs, part of total plasma energy, Q_{ELM} of ≈1–10% of core plasma energy Q_o, is released to SOL at midplane and deposited on divertor surface in a duration τ_{ELM} of ≈0.1–1 ms with a frequency of ≈1–10 Hz. The incoming power from SOL to divertor plate in ITER-like devices during an ELM can then increase from ≈5 MW/m^2 to ≈300–3000 MW/m^2. The erosion losses of divertor materials depend strongly on the power deposited. At low power deposition the surface temperature may not exceed melting temperature, and mass losses due vaporization are small, but particle sputtering and plasma contamination from vapor expansion may be a concern. At high Q_{ELM}, however, the resulting high surface temperature causes vapor cloud formation with similar consequences to plasma disruptions [1]. Vapor cloud decreases net energy deposition at the surface but increases radiation flux to nearby components. Metallic PFCs will melt, and both melt flow and splashing can then occur with mass losses significantly exceeding vaporization losses [4].

A comprehensive two-fluid model in multidimensional geometry is enhanced to include detail atomic physics data for tungsten, lithium, and neon and to integrate core, SOL parameters, and PFC surface evolution (melting, vaporization, vapor cloud hydrodynamics and mixing with plasma particles, and liquid droplet ejection) for low and high power deposition during ELMs and disruptions using the upgraded HEIGHTS numerical simulation package. The transient models include material bulk thermal and mechanical response, surface melt layer formation, near-surface vapor formation and evolution, comprehensive photon line and continuum radiation transport, atomic and molecular processes of surface materials in the plasma, and photon radiation/vapor motion effects on nearby components and the resulting secondary damage [1].

ELMs mitigation by using liquid Li surface and by neon gas puffing above the tungsten divertor surface was evaluated using the HEIGHTS package taking into account detailed photon radiation transport of both lines and continuum radiation in the vapor/neon produced plasma. The transport of impurity vapor from either

* Corresponding author.
E-mail address: hassanein@purdue.edu (A. Hassanein).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2009.01.206

vapor divertor material or neon gas is also modeled to assess plasma contamination. Initial results indicate that high power, i.e., giant ELMs in ITER-like machines can cause serious damage to PFCs, may terminate plasma in disruptions, and because of potential large contamination may affect subsequent plasma operations.

2. Energy transport during ELMs

The HEIGHTS package consists of numerous integrated models that follow the early stages of a plasma disruption/giant ELM in the plasma and scrape-off-layer up to the transport of the eroded debris and splashed target materials as a result of the deposited energy. For the transport of the lost energy from core plasma energy to SOL, it is simply assumed that it occurs within a region of radii from R_{ELM} to R_s (radius at Separatrix). The Q_{ELM} is, therefore, equal to the plasma energy contained between R_{ELM} and R_s. The ELMs parameters are calculated as a function of radial position starting from the Separatrix and going inward to R_{ELM} towards the center [5]. This concept corresponds to the conventional ELM build up scenario of particles expelled from the pedestal region [6]. Other models of energy transport during ELMs can be easily implemented in HEIGHTS.

The large increase in both particle and heat flux, i.e., much higher than normal operation will result in significant increases in mass losses of divertor plate (vaporization, sputtering, brittle destruction, and liquid splashing). To predict these losses and potential contamination of core plasma, two main problems should be addressed, i.e., dynamics and structure of particles in SOL and then the interaction of particle/heat fluxes from the SOL with divertor plate materials.

During normal operation the plasma in SOL is highly collisional, but during ELMs, the mean free path is much larger than the connection length between parallel divertor plate and the SOL plasma becomes collisionless and has different behavior than during normal operation [5]. One main feature of collisionless SOL plasma is the edge plasma acts as an electrostatic trap for electrons. Electrons that originally have parallel energy that is lower than the wall potential energy will be trapped between the inner and outer divertor plates. To obtain the potential and corresponding net heat flux of ions and electrons to the divertor plate we used our previously developed model [5]. The ions escaping the SOL will arrive at the divertor surface with an enhanced energy due to acceleration in the negative potential nearby the plate. The ions, therefore, take part of the ELM electron energy as a result of such acceleration. This potential is less than the ambipolar one due to both the secondary electron emission at the target surface and the existing trapped electrons [5]. Correspondingly, the incident electron energy flux decreases by the same amount needed to build up the electrostatic sheath, therefore, the total energy flux is conserved.

The density, electron temperature, and incident power for typical tokamak parameters of $R_{major} = 600$ cm, a (minor radius) = 200 cm, $T_0 = 10$ keV, and $n = 10^{14}$ cm^{-3} are then calculated by solving mass conservation equation [5]. The distribution of energy deposited at the midplane is calculated assuming that the deposition is due to diffusion with an effective diffusion coefficient of $D \approx 5\ m^2/s$, which corresponds to data obtained by averaging on different shots at various machines [7–9]. The spatial distribution of both the electron and ion heat fluxes released at midplane is calculated using HEIGHTS and have a maximum of 1.0 and 3.5 MW/cm^2 respectively [5]. These values will then determine the hydrodynamic surface evolution of the divertor plate.

3. Interaction of incident particles with divertor surface

The integrated HEIGHTS package that solves detail particle energy deposition, evolution of surface materials, debris formation, vapor MHD, atomic physics and radiation transport, and erosion physics is enhanced and used in this analysis. The enhancement includes development of multidimensional geometry with two-fluid hydrodynamic mixing model where the incident DT plasma is treated separately from the eroded debris cloud of divertor materials. Because of recent interest of using W as PFC material, we performed in this study similar analysis of the effect of ELMs as on C and Be [5]. Fig. 1 shows W surface temperature and resulting melt layer thickness as a result of a giant ELM ($Q_{ELM} \approx 10\%\ Q_0$) of 1 ms duration. Similar to C, W vaporization in this case is low compared to Be surface. The W surface will, however, melt with thickness of 100 μm developed and existing well beyond the duration of the ELM. Figs. 2 and 3 show W surface temperature as a function of ELM intensity and deposited energy at the divertor surface, respectively. Tungsten will start to melt for giant ELMs of energy Q_{ELM} (released at midplane) >8% Q_0. In this situation melt layer erosion and splashing due to various mechanisms are a concern [1]. Carbon may also suffer macroscopic erosion from brittle destruction particularly at higher power deposition and W will also have significant vaporization losses similar to C at shorter giant ELM durations [5].

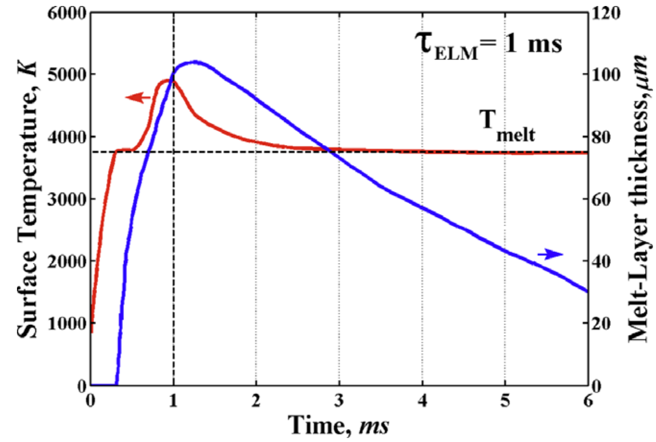

Fig. 1. Tungsten surface response and melt layer thickness due to a giant ELM with 1 ms-duration.

4. ELM mitigation by using liquid metal surfaces and neon gas injection

Using liquid metal surfaces such as Li could be an ideal solution to accommodate plasma instabilities and the associated high heat

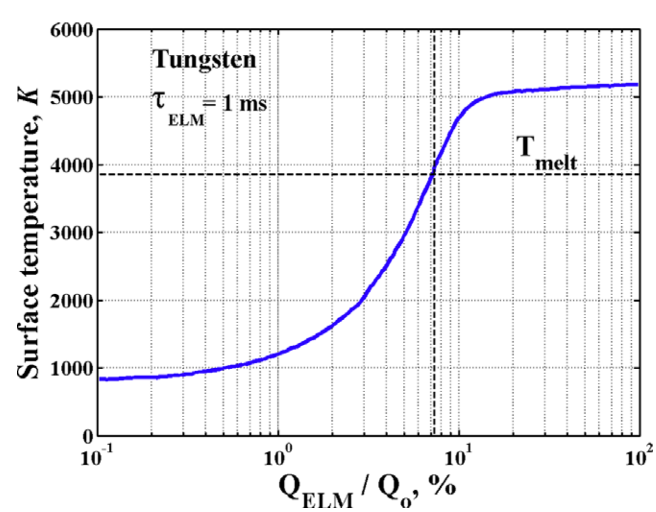

Fig. 2. Tungsten surface temperature as a function of ELM intensity for 1 ms-duration.

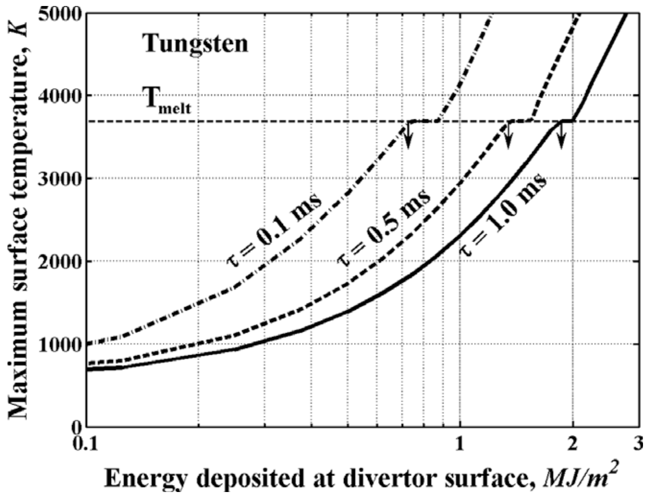

Fig. 3. Maximum tungsten surface temperatures as functions of ELM intensity for 0.1, 0.5, and 1 ms ELM-durations.

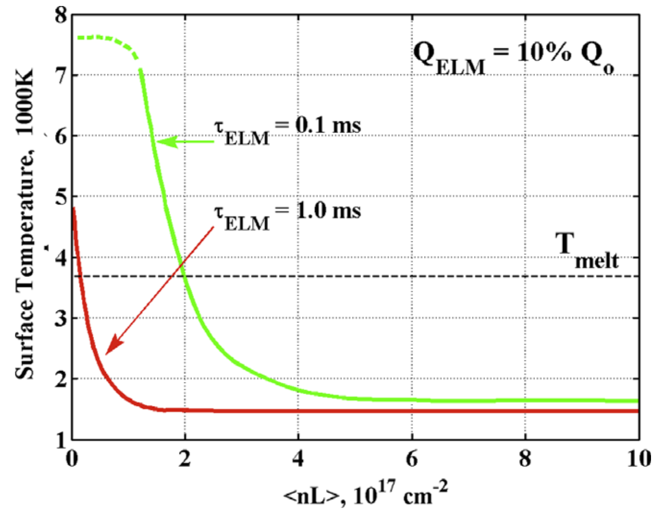

Fig. 5. Tungsten surface response to giant ELM as a function of Neon gas density above the surface.

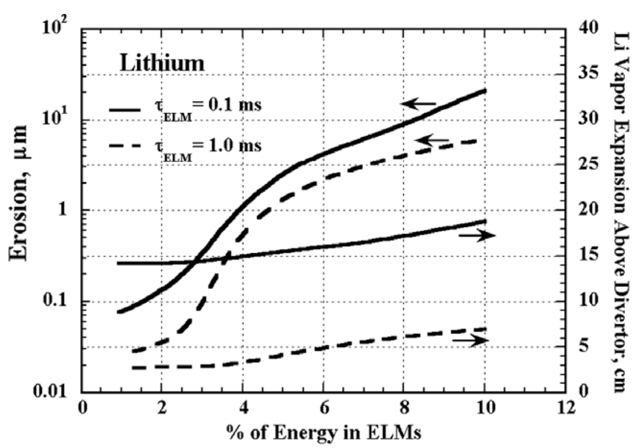

Fig. 4. Liquid Li response to an ELM with different% of Q_o deposited in 0.1 and 1 ms.

and particle fluxes. This can be used and engineered only on areas exposed to extreme heat conditions with minimum effect on overall divertor design. Being replenishable and low-*z*, erosion lifetime is not a major issue and a thin layer on the divertor surface will fully protect it against giant ELMs and disruptions.

Fig. 4 shows Li erosion and expansion distance above the surface for various ELM energies deposited at 100 µs and 1 ms. Lithium erosion rate and expansion are significantly higher at shorter ELM durations. For the extreme giant ELM condition with 100 µs, more than 20 µm is needed due to vaporization to protect the surface below. The real front of the expanding vapor cloud consists mainly of DT particles with high conductivity that results in less diffusion and, therefore, higher cloud-pressure to confine Li vapor expansion above the divertor. This can limit contamination of plasma through SOL [5]. Because the temperature of Li surface can exceed the threshold for splashing due to bubble formation and explosion during high power ELMs, macroscopic losses in from of liquid droplets can also take place [1] and much larger Li thickness may be needed to fully protect the divertor.

HEIGHTS also simulated ELM mitigation using neon gas cloud puffed above the tungsten divertor surface with taking into account full radiation transport of photons both line and continuum spectra in the neon produced plasma. The noble gas should have enough linear density, <nL>, to stop incoming particles, both ions and electrons, and to irradiate significant part of their energy. Numerical simulations were made to evaluate W surface response when exposed to giant ELM but with a layer of neon gas with linear density <nL> immediately above the surface. The simulation showed that the charge of neon cloud plasma formed due to ELM interaction is significantly decreased due to the presence of DT plasma coming from the SOL. This is because the DT particles stopped at the upper neon layer will shield the DT-neon enriched-layer from further heating and ionization of neon. This results in a decrease of total neon cloud radiation, therefore, reducing its effectiveness to protect the divertor plate. Fig. 5 shows the dependence of W surface temperature on neon cloud linear density for two different giant ELM duration times. It is shown that neon shielding efficiency becomes more effective for <nL> > 10^{17} cm^{-2} with asymptotic W surface temperature of around 1500 K. Besides the difficulty of engineering neon gas puffing over a large divertor surface, having <nL> exceeding 10^{17} cm^{-2} is quite high and may present a problem for plasma contamination.

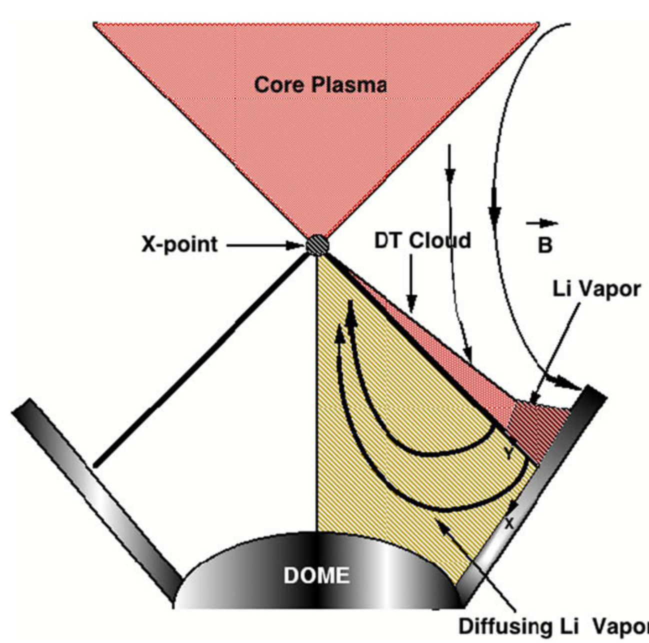

Fig. 6. Schematic illustration of vapor diffusion in lower region of divertor plate.

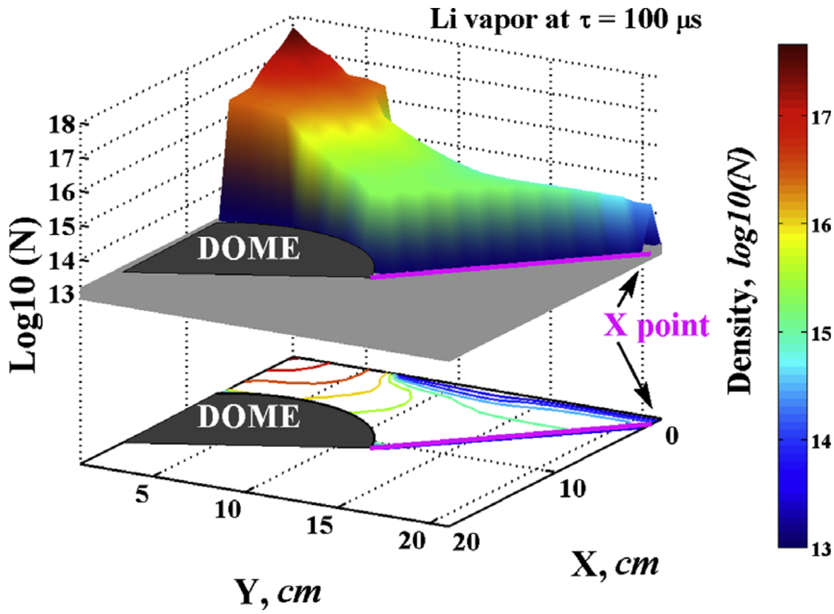

Fig. 7. Spatial distribution of Li vapor diffusion to *X*-point.

5. Diffusion of vaporized material toward *X*-point

Plasma contamination with divertor materials, Li vapor, or gas puffing to mitigate ELMs is a critical concern during ELMs. The expanding vapor cloud consists from two regions: pure vapor cloud existing nearby the divertor surface, and DT cloud above it. The accumulated DT particles above the expanding Li cloud arriving from the SOL plays favorable role, first, as a shield for Li vapor further direct heating, for example, from incident plasma particles, and, second, as a shield for core plasma contamination from the expanding vapor impurities. Thus, even for giant ELMs, Li particles may not reach the separatrix through SOL during the ELM duration.

However, in this analysis a different reason of core plasma contamination is considered, i.e., vapor with high density and low temperature that can diffuse across separatrix, nearby divertor surface, and propagate toward the *X*-point in dome private flux region as illustrated in Fig. 6.

Fig. 7 shows the result of vapor expansion near dome area after 100 μs. The Li vapor can easily diffuse toward the *X*-point because of both the initial low temperature nearby separatrix and decreasing of vapor temperature in dome region due to radiation. For ELM duration of about 100 μs the vapor cloud reaches the *X*-point with rather high density of 10^{14}–10^{15} cm^{-3} in a short time that is comparable to the ELM duration. This may mean that core contamination is possible from regions nearby the *X*-point. Such process of high density vapor diffusing nearby the separatrix is less important in current tokamaks than in future high power machines such as ITER, because of relatively low heat/particles fluxes where intense vaporization threshold depends on power load. Nevertheless, it is important to measure vapor particles concentration in dome region during ELMs in current machines to confirm above modeling results.

6. Summary

High power transients such as edge-localized modes (ELMs) are a serious concern for plasma-facing components during normal operation of next generation tokamaks. A full two-fluid and multi-dimensional model is enhanced with detail atomic physics data for tungsten, Li, and neon to integrate SOL parameters during ELMs with divertor surface evolution (melting, vaporization, vapor cloud dynamics, and macroscopic erosion) using HEIGHTS numerical simulation package. High power ELMs cause excessive target erosion of candidate materials such as Be, C, and W. Tungsten will start to melt for giant ELMs of energy $Q_{ELM} > 8\%\ Q_0$ and 1 ms duration. A thin layer of Li (<1 mm) can fully protect the divertor surface from giant ELMs. However, Li vapor expansion can lead to plasma contamination even when Li erosion lifetime is not a concern. The shielding effect of noble gas puffed above divertor surface is inefficient in protecting the surface due to its less radiative ability than lighter elements (Li, Be, C). For example, a significant amount of neon gas ($nL > 10^{17}$ cm^{-2}) is needed to prevent tungsten surface from melting during giant ELMs. A more serious concern has to do with whether the needed massive gas injection can be retained in the divertor area. In addition, diffusion of impurity vapor, Li atoms, and neon gas across Separatrix in private flux region may result in high level impurities back diffusion toward the *X*-point, thus contamination of core plasma can also occur from region nearby the *X*-point and possibly lead to plasma termination in a disruption.

Acknowledgment

Work is supported by the U.S. Department of Energy, Office of Fusion Energy Science.

References

[1] A. Hassanein, Fusion Eng. Des. 60 (2002) 527.
[2] A. Hassanein, T. Sizyuk, M. Ulrickson, Fusion Eng. Des. 83 (2008) 1020.
[3] A. Hassanein, T. Sizyuk, Nucl. Fusion 48 (2008) 115008.
[4] A. Hassanein, I. Konkashbaev, J. Nucl. Mater. 273 (1999) 326.
[5] A. Hassanein, I. Konkashbaev, J. Nucl. Mater. 313–316 (2003) 664.
[6] M.E. Fenstermacher, ELM Electron and Ion Particle and Energy transport in Tokamak SOLs and Divertors, EU–US TTF Workshop, Cordoba, Spain, 9–12 September, 2002.
[7] A.W. Leonard, R.J. Groebner, M.A. Mahdavi, et al., J. Plasma Phys. Controlled Fusion 44 (6) (2002) 945 (Special issue on the IAEA Technical Committee on Divertor Concepts).
[8] J. Neuhauser, D. Coster, H.U. Fahrbach, et al., J. Plasma Phys. Controlled Fusion 44 (6) (2002) 945 (Special issue on the IAEA Technical Committee on Divertor Concepts).
[9] D.L. Rudakov, J.A. Boedo, R.A. Moyer, et al., Plasma Phys. Control. Fus. 44 (6) (2002) 855 (Special issue on the IAEA Technical Committee on Divertor Concepts).