Fusion Engineering and Design 85 (2010) 1331–1335

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Impact of various plasma instabilities on reliability and performance of tokamak fusion devices

A. Hassanein*, T. Sizyuk, V. Sizyuk, G. Miloshevsky

School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Available online 18 April 2010

Keywords:
Disruption
ELM
VDE
Runaway electrons
HEIGHTS

ABSTRACT

Plasma instability events such as disruptions, resulting runaway electrons, edge-localized modes (ELM), and vertical displacement events (VDE) are mainly the most limiting factor for successful tokamak reactor concept. The plasma-facing components (PFC), e.g., wall, divertor, and limited surfaces of a tokamak as well as coolant structure materials are subjected to intense particle and heat loads and must maintain a clean and stable surface environment between them and the core/edge plasma. This is critical to fusion device performance. Comprehensive research efforts are developed utilizing the HEIGHTS simulation package to study self-consistently various effects of high power transient on material operation/selection. The package consists of several models that integrate different stages of plasma–wall interactions starting from energy release at scrape-off-layer and up to the transport of the eroded debris and splashed wall materials as a result of the deposited energy. The integrated model predicts material loss, PFC lifetime from transients, and effects on core plasma performance. HEIGHTS initial simulation shows that a single event such as a major disruption, VDE, or runaway electron could severely damage the reactor wall and structural materials and disrupt operation for a significant time. HEIGHTS is used to identify safer operating window regimes and upper transient limits that PFC can withstand during various instabilities.

1. Introduction

Various damage to plasma-facing components (PFM) as a result of plasma instabilities still remains a major obstacle to a successful tokamak reactor design. Loss of plasma confinements and instabilities take various forms, such as major disruptions, which include both thermal and current quench (sometimes producing runaway electrons); edge-localized modes (ELM), and vertical displacement events (VDE). Most plasma instabilities may cause both surface and bulk damage to plasma-facing and structural materials [1]. Surface damage mainly consists of high erosion losses attributable to surface vaporization, spallation, and melt-layer erosion. Major bulk damage of plasma instabilities, particularly those of longer duration, such as VDE, or those with deeper deposited energy, such as runaway electrons, is the result of the high heat flux reaching the coolant channels, possibly causing burnout of these tubes [2–4]. Additional bulk damage may include 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, melting and detachment of surface coating material, and material fatigue and failure. In addition to these effects, the transport and redeposition of the eroded surface materials to various locations on PFC are of major concern for plasma contamination, safety (dust inventory hazard), and successful and prolonged plasma operation after instability events [5].

The HEIGHTS package has been developed as an instrument and comprehensive tool for the simulation and optimization of the interaction processes during the intense energy deposition of various energy sources such as plasma, laser, and particle beams incident on target materials. The HEIGHTS package has 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. The enhanced transient models include 3D energy deposition and material bulk thermal response, 3D thermal hydraulic analysis of coolant channels, surface melt-layer formation and movement, near-surface vapor-shield formation and evolution, 3D 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. Recently, HEIGHTS investigated in detail the effects of plasma instabilities including VDEs [2,6], ELMs [7], disruptions [1,8] and runaway electrons [9] on plasma-facing components (PFC) of a tokamak reactor and analyzed ways for mitigating such effects. The simulation results showed that disruptions and high power ELMs cause excessive target erosion of candidate

---

* Corresponding author. Tel.: +1 765 496 9731; fax: +1 765 496 2233.
E-mail address: hassanein@purdue.edu (A. Hassanein).

0920-3796/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2010.03.039

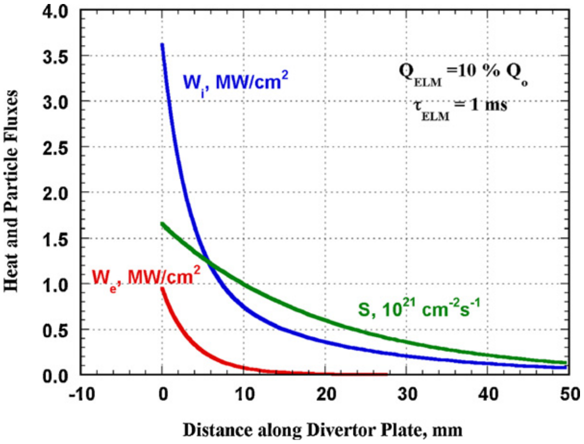

Fig. 1. Calculated spatial distribution of particle flux S, electron heat flux W_e, and ion heat flux W_i during an ELM [12].

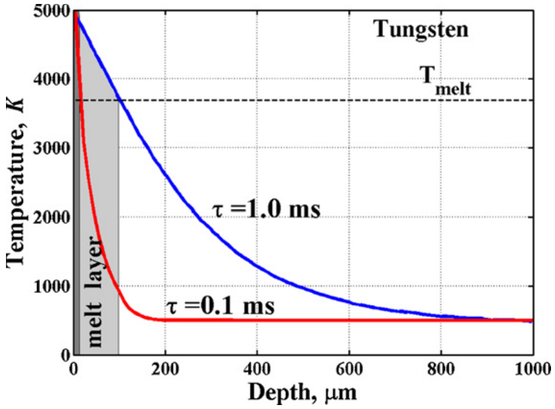

Fig. 2. Temperature distribution in W divertor at the end of heat load at giant ELM of 0.1 ms and 1 ms durations.

materials and possible plasma contamination. The long impact of plasma energy of VDE can cause melting of structure and burnout of coolant tubes. Runaway electrons penetrate deeper into first wall with Be coating and result in melting and damage of Be/Cu interface. On the other hand, W coating if possible for the first wall will protect the structural material but the tungsten armor will suffer significant melting and splashing causing.

2. Integrated simulation of plasma surface interaction during ELMs and disruptions

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 scrape-off-layer (SOL) and then the interaction of particle/heat fluxes from the SOL with divertor plate materials. During ELMs [10,11], the mean free path is much larger than the connection length between parallel divertor plates and the SOL plasma becomes collisionless and has different behavior than during normal operation [12]. In the collisionless SOL plasma 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 [12]. 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. 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 the major radius of 600 cm, the minor radius of 200 cm, T_0 = 10 keV, and $n = 10^{14}$ cm^{-3} are then calculated by solving mass conservation equation [12]. 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.

Fig. 1 shows calculated values which then determine the hydrodynamic surface evolution of the divertor plate. Because of recent interest of using W as PFC material, we performed similar analysis of the effect of ELMs as on C and Be [12,7]. Fig. 2 shows W temperature distribution and melt-layer thickness at the end of a giant ELM ($Q_{ELM} \approx 10\%\ Q_0$) of 0.1 and 1 ms durations. Similar to C, W vaporization in case of longer giant ELM duration is low compared to Be surface. The W surface will, however, melt with thickness 100 μm developed and existing well beyond the duration of the ELM 1 ms duration. W will also have significant vaporization losses similar to C at shorter giant ELM durations with melting layer thickness of about 15 μm (Fig. 2).

Using liquid metal surfaces such as Li could be an ideal solution to accommodate plasma instabilities and the associated high heat 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. For the extreme giant ELM condition with 100 μs, approximately 20 μm is needed due to vaporization to protect the surface below [7]. 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.

However, Li vapor expansion can lead to plasma contamination even when Li erosion lifetime is not a concern. 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 [12]. Thus, even for giant ELMs, Li particles may not reach the separatrix through SOL during the ELM duration. On the other hand, vapor with high density and low temperature can diffuse across separatrix, nearby divertor surface, and propagate toward the X-point in dome private flux region. 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.