Damage to nearby divertor components of ITER-like devices during giant ELMs and disruptions

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2010 Nucl. Fusion 50 115004
(http://iopscience.iop.org/0029-5515/50/11/115004)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 128.46.102.187
The article was downloaded on 30/03/2011 at 14:14

Please note that terms and conditions apply.
Damage to nearby divertor components of ITER-like devices during giant ELMs and disruptions

V. Sizyuk and A. Hassanein

Purdue University, West Lafayette, IN 47907, USA
E-mail: vsizyuk@purdue.edu (V. Sizyuk) and hassanein@purdue.edu (A. Hassanein)

Received 12 May 2010, accepted for publication 16 August 2010
Published 13 September 2010
Online at stacks.iop.org/NF/50/115004

Abstract

During normal operation of the high confinement mode in future ITER devices, edge-localized modes (ELMs) are a potential threat to the divertor components lifetime and plasma contamination. To predict the outcome of the direct ELM plasma impact on the divertor plate, conversion of plasma energy into radiation in the shielding layer, and then the resulting energy deposition of radiation flux to the surrounding areas, comprehensive physical and numerical models are developed and implemented in the HEIGHTS package. The energy deposition, divertor material erosion, resulting vapour plasma temperature and density evolution, and subsequently the resulting radiation, its transport and deposition around the divertor area are calculated for the predicted ELM and disruption parameters and for the prospective full ITER geometry. The initial simulation results showed that the disrupted plasma power density at the original divertor location and vapour radiation fluxes on nearby dome locations can have the same order of magnitude. The simulation results of the integrated modelling indicate a significant potential damage of the divertor nearby surfaces during giant ELMs and disruption impacts for ITER-like parameters and geometry.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Damage to plasma facing components (PFCs) and structural materials due to loss of plasma confinement in tokamak devices remains one of the most serious concerns for safe, successful and reliable reactor operation. Plasma instabilities occur in various forms such as hard disruptions, which include both thermal and current quench, edge-localized modes (ELMs), runaway electrons and vertical displacement events (VDEs). The extrapolation of heat loads on the PFCs during disruptions and ELMs to ITER parameters indicates serious consequences of these phenomena. To mitigate the damage risk, ITER Research Plan [1] included development of local models taking into account surface shaping and attempting to predict the observed deposition patterns. Because disruptions and ELMs are the focus of increasing attention by the edge physics community due to the large divertor heat loads, these events would have significant influence on the divertor design of future ITER-like devices [2–6]. A main attribute of the type I ELM is the periodic large power loads on PFCs. The study of the pedestal structure collapse due to an ELM is important for understanding its mechanism and reduction of its severe heat loads on the divertor target, which can erode the divertor plate and nearby components as well as contaminate the plasma. The extrapolations from existing tokamak devices [7–11] and theoretical modelling [12–14] predict main parameters of the ELM events such as the total energy, temperature of the scrape-off layer (SOL) plasma, duration and frequency of plasma impacts. A major disruption or a giant ELM event has a complex sequence of interaction stages with the tokamak components: part of plasma energy released to SOL, then converted to heat load on the divertor plate, heating/melting/vaporization of the plate, vapour expansion and continued heating from impinging plasma particles, vapour shielding of direct plasma deposition to the plate, conversion of plasma deposited energy into photon radiations, radiation transport in shielding layer and then radiation deposition on nearby components. Therefore, the disruption or ELM event is not only a direct heat load to the divertor and the erosion and plasma contamination will depend on the vapour/plasma shield evolution in the strong and inclined magnetic field at the divertor surface. In this view, configuration/geometry of tokamak wall and divertor components and the magnetic field structure is a key factor in the performance of the tokamak fusion reactor. Our calculations [15] showed much higher temperature of the divertor surface and divertor plasma for the ITER parameters in comparison with the existing current tokamak devices. Drift of the hot plasma in the complex 3D magnetic field configurations in the divertor area translates to a complex heat transport...
onto the divertor nearby components. Because heat loads and disruption conditions of future ITER-like and Demo devices are not achievable in current tokamaks, the main goal of our simulation work is to integrate various modelling processes of disrupting/ELM plasma impact process into realistic reactor geometry to predict and compare the direct heat fluxes on the divertor as well as the secondary radiation fluxes on nearby components for the ITER geometry [16].

We simulated the evolution of an ELM plasma impact onto the divertor of ITER device geometry with magnetic field configuration using the HEIGHTS (High Energy Interaction with General Heterogeneous Target Systems) computer simulation package with integrated models [17–19]. The integrated models included five main parts: Monte Carlo block of disrupting plasma particles interaction with solid and plasma matter; magnetohydrodynamic (MHD) block of plasma evolution taking into account magnetic field diffusion; heat conduction and vaporization block for tokamak PFCs; heat conduction block for vapour and plasma and Monte Carlo radiation transport. The radiation transport block is based on the optical data calculated by the HEIGHTS atomic physics package [20]. The modelling was carried out in the three-dimensional geometry where the toroidal component of all parameters was integrated due to the invariability of disruption/ELM impacts along the divertor toroidal direction.

2. Mathematical and physical models

The HEIGHTS model of plasma particles interaction with matter is described in detail in [17, 21, 22]. The three-dimensional Monte Carlo algorithm is developed and benchmarked for plasma particles interactions with solid and plasma matter in magnetic field in any geometrical configuration. The heat conduction and vaporization block simulates heat transfer, melting and surface vaporization of target due to various input energy sources [23]. Heat conduction in plasma is developed using an implicit algorithm of the sparse matrix technology [24, 25]. The radiation transport based on the weighted Monte Carlo method is previously described and benchmarked in detail for laser and discharge plasma [26–28].

All various blocks are integrated into common MHD equations system which is given for the three-dimensional case for conservation of mass, pulse, energy and magnetic field as

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = Q_{\text{mass, vap}}, \]
\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} + \rho \mathbf{v} \mathbf{p}) = \frac{\mathbf{B}^2}{4\pi \mu} \mathbf{B} (\nabla \cdot \mathbf{B}), \]
\[ \frac{\partial \mathbf{e}}{\partial t} + \nabla \cdot (\mathbf{e} \mathbf{v} + \mathbf{p}) = \frac{1}{4\pi \mu} (\mathbf{B} \cdot \mathbf{B}), \]
\[ \frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v} \mathbf{B} - \mathbf{B} \mathbf{v}) + \frac{c^2}{4\pi \mu} \nabla \times (\eta \nabla \times \mathbf{B}) = -\mathbf{v} (\mathbf{B} \cdot \nabla). \]

Here, \( \rho \) is the density; \( \mathbf{v} \) is the velocity; \( \mathbf{B} \) is the magnetic field; \( \mathbf{e} \) is the total energy, which includes the hydrodynamic part, \( \mathbf{e}_h = \mathbf{e}_\text{kin} + \mathbf{e}_\text{int} \) and the magnetic part \( \mathbf{e}_m = (\mathbf{B}^2/8\pi \mu) \); \( \mathbf{e}_\text{kin} \) is the internal energy; \( \mathbf{e}_\text{int} = (\rho \mathbf{v}^2/2) \) is the kinetic energy. Analogous to energy, pressure has hydrodynamic and magnetic parts: \( \mathbf{p}_h = \rho_h + (\mathbf{B}^2/8\pi \mu). \) Magnetic diffusion processes are taken into account as the Joule heat term, \( (c^2 \eta/16\pi^2 \mu^2) \nabla \times (\eta \nabla \times \mathbf{B}) \), in the total energy equation and as the diffusion term, \( (c^2/4\pi \mu) \nabla \times (\mathbf{v} \nabla \times \mathbf{B}) \), in the magnetic field equation, where \( \eta \) is the resistivity, \( \mu \) is the magnetic permeability and \( c \) is the light speed. In the calculations below we assume \( \mu = 1 \) for the plasma. The thermal conduction in the plasma is included as \( Q_{\text{th}} \) term in the energy equation. The target vaporization process is taken into account as \( Q_{\text{mass, vap}} \) and \( Q_{\text{dis, vap}} \) sources in continuity and energy equations correspondingly. The \( Q_{\text{rad}} \) term describes the radiation transport processes and \( Q_{\text{amp}} \) is the external energy source that takes into account energy input from the ELM plasma particles. The right-hand side terms of equations, which contain magnetic field divergence \( (\nabla \cdot \mathbf{B}) \), are included for the magnetic field correction [29, 30]. We use Gaussian units unless indicated otherwise.

Because the plasma parameters are assumed invariable along the divertor surface in the toroidal direction we take into account zero derivatives of all variables in the y-direction (see figure 1 for outer divertor plate). Here we assumed the x-axis as the poloidal, y-axis as the toroidal and z-axis as the radial directions. Since the common equation (1) combines all physical processes as convective (hydrodynamic flux) and dissipative (heat conduction, radiation transport, disruption plasma impact), we used splitting of the physical processes
in our numerical algorithm to separate the hyperbolic and parabolic parts [24, 25, 31].

The separated from equation (1) convective part in the coordinate system \( S(x, y, z) \) after transformations is presented in matrix form and solved following the total variation diminishing scheme in the Lax–Friedrich formulation (TVD-LF) [27, 30]. Full description of the MHD cell state includes eight variables: \( U(\rho, \rho v_x, \rho v_y, \rho v_z, e, B_x, B_y, B_z) \) and the matrix expression is given as

\[
\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial H(U)}{\partial z} = \Omega, \tag{2}
\]

where flux \( F \) is determined as

\[
F(U) = \begin{bmatrix}
\rho v_x \\
\rho v_x^2 + p_x - B_x^2/4\pi \\
\rho v_x v_y - B_y B_z/4\pi \\
\rho v_x v_z - B_x B_z/4\pi \\
v_x(e_i + p_i) - B_x(B_v x + B_y v_y + B_z v_z)/4\pi \\
0 \\
v_x B_y - B_x v_y \\
v_x B_z - B_x v_z \\
\end{bmatrix},
\]

and flux \( H \) is expressed as

\[
H(U) = \begin{bmatrix}
\rho v_z \\
\rho v_z v_x - B_y B_z/4\pi \\
\rho v_z v_y - B_x B_z/4\pi \\
\rho v_z^2 + p_z - B_z^2/4\pi \\
v_z(e_i + p_i) - B_z(B_v x + B_y v_y + B_z v_z)/4\pi \\
0 \\
v_z B_y - B_z v_y \\
v_z B_z - B_z v_z \\
\end{bmatrix}.
\]

We included the dissipation processes \( Q \) presented above into common external source \( \Omega \):

\[
\Omega = \begin{bmatrix}
\frac{Q_{\text{m, vap}}}{4\pi} & -\frac{B_y}{4\pi} \frac{\partial B_y}{\partial x} + \frac{\partial B_y}{\partial z} \\
-\frac{B_y}{4\pi} \frac{\partial B_x}{\partial x} + \frac{\partial B_x}{\partial z} \\
\frac{B_x}{4\pi} \frac{\partial B_y}{\partial x} + \frac{\partial B_y}{\partial z} \\
\frac{B_x v_x + B_y v_y + B_z v_z}{4\pi} \left( \frac{\partial B_x}{\partial x} + \frac{\partial B_z}{\partial z} \right) \\
-\frac{v_x}{4\pi} \frac{\partial B_x}{\partial x} + \frac{\partial B_x}{\partial z} \\
-\frac{v_y}{4\pi} \frac{\partial B_y}{\partial x} + \frac{\partial B_y}{\partial z} \\
-\frac{v_z}{4\pi} \frac{\partial B_z}{\partial x} + \frac{\partial B_z}{\partial z} \\
\end{bmatrix}.
\]

Equation (2) does not include the magnetic field diffusion processes. However, the magnetic diffusion corrections should be performed in the energy and Faraday equations of the MHD system as is described in [25]. The magnetic diffusion equations have parabolic type and for its solution we used an implicit scheme based on the sparse matrix technology [24, 27]. The solution of the magnetic diffusion equation determines dissipative changes in the magnetic field that should be used to correct the MHD vector \( U \). The magnetic diffusion system for our coordinate system and for the made assumptions is given as

\[
\begin{align*}
\frac{\partial B_x}{\partial t} + \frac{\partial \eta c^2}{\partial x} \left( \frac{\partial B_x}{\partial x} - \frac{\partial B_y}{\partial z} \right) &= 0, \\
\frac{\partial B_y}{\partial t} + \frac{\partial \eta c^2}{\partial x} \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_z}{\partial z} \right) &= 0, \\
\frac{\partial B_z}{\partial t} + \frac{\partial \eta c^2}{\partial x} \left( \frac{\partial B_z}{\partial x} - \frac{\partial B_y}{\partial z} \right) &= 0.
\end{align*}
\tag{6}
\]

The parabolic equation (6) was presented as an elliptic equation for one hydrodynamic time step \( n \) [25]. Solution of equation (6) gives the magnetic field dissipative change in time step \( n: \Delta B^n = B^{n+1} - B^n \). The magnetic fields time step variation \( \Delta B^n \) was used for correction of the MHD system in equation (2). This MHD equation system is solved using the TVD-LF algorithm described in [23, 27, 30]. Used in this numerical scheme the maximum propagation speed of information (see [30] for details) for the tokamak divertor case is given as

\[
c_i^{\text{max}} = |v_i| + \left[ \frac{1}{2} \left( \frac{v_{\text{ac}}^2 + B_x^2 + B_y^2 + B_z^2}{4\pi\rho} \right) + \left( \frac{v_{\text{ac}}^2 + B_x^2 + B_y^2 + B_z^2}{4\pi\rho} \right)^2 - \frac{v_{\text{ac}}^2 B_z^2}{\pi\rho} \right]^{1/2} \right],
\tag{7}
\]

where index \( i = x, z \) determines the spatial direction: \( x \) for the flux \( F \) and \( z \) for the flux \( H \) calculations; \( v \) is the media velocity and \( v_{\text{ac}} \) is the speed of sound.

3. Divertor geometry and computation domain setup

The ITER design submitted to the ITER Parties as the ‘ITER-Feat Outline Design Report’ in January 2000 [16] is taken as the basic geometry for our simulations. In this design, the divertor is made up of separate cassettes. Figure 2 schematically shows the configuration of the target and divertor area and the large opening between the inner and outer divertor.
legs to allow an efficient exchange of neutral particles. The current design analysis assumes carbon material at the vertical strike points. For our calculations, we used properties of the POCO AXM 5Q graphite [32]. We assumed the magnetic field inclined angle to the divertor surface at the strike point to be 5° [5]. To determine the final spatial direction of the magnetic field, the angle between the separatrix and the x-axis was calculated. The magnitude of magnetic field in our modelling was assumed to be 5 T at the strike point.

The ELM plasma impact is simulated in our Monte Carlo algorithm as the deuterium–tritium plasma particles flow in the magnetic field along the separatrix line. The spatial distribution of the ELM plasma impact is modelled exponentially along the strike point as described in [19]. This spatial distribution keeps the maximum of power deposition at 4.62 MW cm$^{-2}$ near the divertor strike point for the 0.1 ms ELM duration and 12.6 MJ of total ELM energy (∼10% of the pedestal energy [5]). The e-fold length of the plasma power profile above the divertor plate was ∼6.7 cm for these conditions. The major radius in ITER geometry was 6.5 m. The ELM durations of 0.5 ms and 1.0 ms correspond to deposition powers of 0.92 MW cm$^{-2}$ and 0.46 MW cm$^{-2}$, respectively. The initial temperature of the ELM plasma was taken as 3.5 keV [5]. The Monte Carlo algorithm included modelling of the ELM plasma particles interaction with the divertor solid target, divertor vaporized gas and the divertor plasma in magnetic field configuration. The heat conduction and vaporization block modelled the ELM energy redistribution in the divertor target area and the inflow of the vaporized material magnetohydrodynamic evolution. The MHD domain integrates modelling of the plasma hydrodynamic evolution, magnetic diffusion, heat conduction and radiation transport. The detailed description of plasma evolution and plasma properties calculations are described in [20–25]. The carbon plasma opacities were calculated with the HEIGHTS atomic physics package [20] and combined in 3800 spectral groups to provide maximum accuracy for radiation transport calculations. The minimum cell size was 500 µm for the MHD modelling above the divertor surface and 1 µm under the divertor surface for accurate description of the ELM impact energy deposition profile.

4. Simulation results

4.1. Giant ELM

The integrated multidimensional modelling of the ELM impact effects in the more realistic ITER geometry used in this analysis confirmed the erosion losses for the carbon-based divertor material that was reported in our previous simulations [19, 33]. However, we should indicate the presence of the strong spatial dependence of the erosion profile that cannot be described with simple lower-dimensional processes. The complex character of the magnetic field plasma drift in the divertor nearby areas did affect the shielding processes of the target surface plasma. The final divertor surface profiles (see figure 3) are the products of three time-dependent processes: direct impact energy deposition through the unsteady divertor plasma cloud; secondary radiation of the hot plasma cloud and the thermal relaxation of heat conduction inside the divertor plate.

The behaviour of these three processes is different for both the short and the long plasma impact durations. The shorter ELM impact duration (0.1 ms) initiates intense surface vaporization. The produced plasma cloud has high temperature (up to 60 eV) and is very effective in forming a stable shield for the ELM incoming particles because of the insufficient time for vapour MHD motion and transport. The plasma shield acts as an absorptive layer for the ELM impact at the strike point location. The ELM particles decelerate, scatter and deviate from the initial impinging direction in the plasma cloud that results to a decrease in the erosion depth directly at the strike point and to a broadening of the whole erosion area. Because the plasma cloud is located near the strike point and has a relatively stable position, the second process of the plasma radiation is evolved in this closed area around the divertor strike point and relatively far from the nearby components. The impact ELM energy is consumed mostly for vaporization because of insufficient time for thermal relaxation inside the divertor plate. Figure 4 shows the erosion profile combined with the time integrated energy fluxes (direct ELM impact and plasma cloud radiation) for the 0.1 ms ELM impact. The time evolution of these fluxes is shown in background colours with the time scale given in the right side of the figure. The magnetohydrodynamic role of the evolved vapour plasma increases appreciably with the ELM impact duration. The plasma cloud has time for motion and expansion in the dome area. The effectiveness of plasma shielding is reduced and the erosion area concentrates closer to the strike point with deeper erosion in this location. The second process of the plasma cloud radiation is combined with the appreciable MHD vapour plasma motion in this case and redirects the ELM impact energy from the strike point area, decelerates divertor erosion, however increases the risk of nearby components damage. The net erosion damage profile strongly depends on both the impact energy and the pulse duration that are sufficient for surface vaporization and plasma cloud formation. The third process of the target thermal relaxation due to heat conduction inside the divertor plate also helps in mitigating the divertor erosion because of the diffused energy inflow. Figure 5 shows the energy fluxes and erosion thickness for the long ELM impact of 1.0 ms. The broadening of the direct ELM energy distribution and the shielding effect for the short impact duration can be shown by comparing figures 4 and 5. The left shift of the secondary radiation in figure 5 indicates...
the important role of the MHD processes for the longer plasma impact. Figure 6 shows the erosion evolution during ELM energy deposition of various durations. The erosion depth (solid line) corresponds to the maximum of the erosion profile and the net erosion curve (dashed line) presents the total vaporized mass. From the short to long impact duration, the effect of the MHD processes increases and the erosion time behaviour reflects the plasma shield hydrodynamics efficiency.

The important role of the hydrodynamics processes at the longer impact duration is illustrated in figure 7. The vector field of the plasma drift velocity \(v_{xz}\) is plotted in the background of the current radiation fluxes field. Figure 7(a) verifies the radiation fluxes localization near the strike point for the shorter ELM and figure 7(b) shows the distributed radiation fluxes at the nearby components in the case of longer ELM duration. The role of the shielding efficiency of the vapour plasma increases significantly with the plasma impact energy.

### 4.2. Disruptions

We simulated the effect of a major disruption having 126 MJ total impact energy (100% pedestal energy) on the carbon divertor plate. Figure 8 shows a significant increase in the radiation part of the total deposited energy compared with the ELM case. A simple figure of estimate for the 5 MW cm\(^{-2}\) starting peak incident plasma flux and a 1 ms impact duration gives an unshielded maximum energy deposition of 5 kJ cm\(^{-2}\). The total net energy deposited at the divertor surface in figure 8 (white line) has a maximum of 250 J cm\(^{-2}\) that is twenty times lower than the initial plasma impact energy flux. For similar analysis of an ELM case, the net energy flux reaching the divertor plate is lower only 2–5 times compared with the incident unshielded energy flux.

For shorter disruption times, i.e. higher energy depositions, the vapour plasma shielding efficiency is very high and a complete cutoff of the direct impact energy incident on the divertor surface is reached in the first 10–20 \(\mu s\) (figure 9). The subsequent plasma disruption energy is completely absorbed in divertor vapour plasma and the erosion processes at the divertor plate is only affected by the radiation fluxes.

### 4.3. Radiation flux at divertor nearby surfaces

One main goal of this work is to calculate the radiation fluxes at ITER divertor nearby surfaces and to estimate the resulting damage during ELM energy depositions. We calculated the incident photon fluxes along the dump and dome surfaces using our Monte Carlo radiation transport model implemented in HEIGHTS. Figure 10 shows photon radiation energy...
depositions for various ELM durations. For the same impact of total ELM energy of 12.6 MJ, higher radiation deposition was predicted for the longer impact duration of 1.0 ms. The maximum energy deposited reaches values up to 40 J cm$^{-2}$. These values are smaller but have the same order of magnitude as the energy depositions given in figures 4 and 5. The heat load at the nearby divertor components increases considerably for the disruption case (see figure 10) which corresponds to the higher direct energy deposited on the divertor plate.

Therefore, we should be concerned about the potential damage risk of the divertor nearby component surfaces and potential plasma contamination during ELM energy deposition with ITER-like parameters and geometry. The final surface erosion will depend on many factors including plasma shielding, the magnetic hydrodynamics effects and material thermal relaxation during the duration of the energy deposition. To study these factors more accurately we are improving our physical and mathematical model to include multi-material composition capabilities for simulation of different divertor and nearby component materials; evolution of MHD, radiation transport and atomic physic for mixed materials; unstructured mesh in divertor dome area for simulating the melting and vaporization processes at any surface location visible to photon radiation and expanding vapour plasma.

5. Conclusions

We have developed physical and mathematical multidimensional integrated models for extensive and integrated
these locations we are improving and updating our physical devices. To evaluate the details of the actual damage over all giant ELMs and disruption energy deposition in ITER-like the potential damage risk of the divertor nearby surfaces during the energy depositions at the divertor surface. This highlights dump and dome locations have a similar order of magnitude as the entire dome area. It was found that the radiation fluxes at the 3D MHD effects on the divertor erosion dynamics in the energy 12.6 MJ. The simulation results showed the influence of three ELM durations in 0.1, 0.5 and 1.0 ms with the same total energy 12.6 MJ. The simulation results showed the influence of mixed materials MHD and radiation transport. simulation of ELMs and disruption plasma impact on the tokamak divertor and nearby locations. The models include Monte Carlo algorithms for plasma particles motion and collision description; total variation diminishing scheme for the magnetohydrodynamics of the evolving divertor plasma; implicit numerical schemes for plasma heat conduction and magnetic field diffusion; weighted Monte Carlo method for plasma radiation transport; mesh refinement method for the divertor surface detailed energy deposition and surface vaporization models. We implemented and integrated these models in our HEIGHTS computer simulation package to study the impact of ELM and disruption plasma energy deposition for ITER-like device parameters and components geometry. We studied three ELM durations in 0.1, 0.5 and 1.0 ms with the same total energy 12.6 MJ. The simulation results showed the influence of the 3D MHD effects on the divertor erosion dynamics in the entire dome area. It was found that the radiation fluxes at the dump and dome locations have a similar order of magnitude as the energy depositions at the divertor surface. This highlights the potential damage risk of the divertor nearby surfaces during giant ELMs and disruption energy deposition in ITER-like devices. To evaluate the details of the actual damage over all these locations we are improving and updating our physical and mathematical models to include mixed materials MHD and radiation transport.

Acknowledgment

This work is supplied by the US Department of Energy, Office of Fusion Energy Sciences.

References

[12] Strait E.J. for the DIII-D Team 2009 Nucl. Fusion 49 104008
[17] Sizyuk V. and Hassanein A. 2009 Nucl. Fusion 49 095003
[33] Hassanein A. 2002 Fusion Eng. Des. 60 527

Figure 10. Energy deposition fluxes at leg and dome surfaces for various durations of (a) ELMs and (b) disruptions.