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Integrated models for ELMs and the effect on plasma-facing components during normal tokamak operation

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Abstract

During normal H-mode operation of the next tokamak generation, edge-localized modes (ELMs) are of serious concern for divertor plasma-facing components (PFCs). During ELMs pulses of energy and particles are transported across the Separatrix to the scrape-off-layer (SOL) and eventually to the divertor surface. ELMs could, therefore, result in cyclic thermal stresses, excessive target erosion, and consequently, shorter divertor lifetime. A two-fluid model has been developed to integrate SOL parameters with divertor surface evolution (melting, vaporization, vapor cloud dynamics, etc) for different ELM parameters using the HEIGHTS numerical simulation package. Initial results indicate that high-power ELMs in ITER-like machines can cause serious damage to divertor components, may terminate plasma in disruptions, and may affect subsequent plasma operations due to large contamination.

I. Introduction

Edge-localized modes (ELMs) are the focus of increasing attention for tokamak reactor design because of the impact of the high power deposited on divertor design and lifetime. The importance of ELMs arises from a number of concerns, such as to limiting energy confinement, providing density control and limiting buildup of impurities, broadening scrape-off-layer (SOL) density profile, causing large heat pulses on the plasma-facing components (PFCs), and increasing the sputtering of divertor materials.

During ELMs, part of the total plasma energy, Q_{ELM} of $\eta \approx 0.01\text{-}0.1$ of core plasma energy Q_o, is released and deposited on the divertor surface over a duration of $\tau_{ELM} \approx 0.1\text{-}1$ ms in ITER-like machines with a frequency of ≈ 10-20 Hz. This energy can consist of a conduction part due to thermal conduction and a convection part carried by the diffusing particles. The incoming power from the SOL to the divertor plate in ITER-like devices during an ELM can then increase from ≈ 5 MW/m^2 to ≈ 300-3000 MW/m^2. The mass losses of divertor materials are strongly dependent on the power deposited [1]. At low power deposition, the surface temperature of the PFC, such as Be and C, will not exceed the melting temperature and mass losses due vaporization are small. However, with an ELM frequency of 10-20 Hz, thermal cycling takes place and can result in thermal stresses and fatigue. At high Q_{ELM}, the resulting high surface temperature causes vapor-cloud formation with similar consequences to plasma disruptions [2]. Vapor shielding decreases energy deposition at the surface but increases radiation flux to nearby components. Metallic PFCs will melt, and both flow instabilities and splashing can occur, with mass losses significantly exceeding atomic vaporization [3].

The mechanisms suggested for the rapid loss of plasma from the core edge during ELMs include parallel convection along suddenly-opened field lines produced by island formation, turbulent radial transport due to electrostatic or electromagnetic fluctuations, and radial convection due to large-scale-length potential structures [4].

It is assumed in our model that the lost core plasma energy to SOL occurs within a region of radii from R_{ELM} to R_S (radius at Separatrix). Therefore, Q_{ELM} is equal to the plasma energy contained between R_{ELM} and R_S. It is also assumed that the energy and particle losses across the magnetic field have a diffusive character with an enhanced diffusion coefficient [1].

II. Model of SOL during ELMs

According to our first assumption one can find the number of particles (DT ions) that escape to the SOL during an ELM, N_{ELM}, corresponding to an energy Q_{ELM}:

$$Q_{ELM} = \int_{R_{ELM}}^{R_s} \frac{3}{2} k\left(T_i + Z_{eff} T_e\right) n_i(r) 2\pi R \cdot 2\pi r \cdot dr = \frac{3}{2} kT_{mean}\left(1 + Z_{eff}\right) \cdot N_{ELM} = \eta Q_o, \quad (1)$$

where T_{mean} is the average temperature of ions and electrons in this region.

Figure 1 shows the predicted ELM relative parameters as a function of radial position starting from the Separatrix (R_S = 200 cm) and going inward to R_{ELM} towards the center [1]. For example, for $Q_{ELM} \approx 1\%Q_0$ (i.e., $\eta = 0.01$), it corresponds to a radius $R_{ELM} = R_S - \Delta R_{ELM}$ = 184 cm and $T_{mean} \approx 1.05$ keV. For $Q_{ELM} \approx 10\%Q_0$ ($\eta = 0.10$), this corresponds to radius R_{ELM} = 164 cm and $T_{mean} \approx 2.4$ keV.

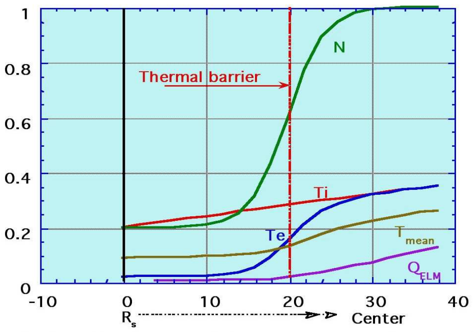

Fig. 1 Predicted ELMs relative parameters as a function of radial position from Separatrix and inward to R_{ELM}

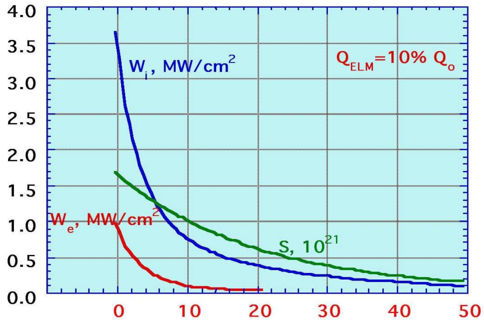

Fig. 2. Calculated spatial distribution of particle flux, S, electron, We, and ion, Wi, heat fluxes during an ELM.

The large increase in both particle and heat flux compared with normal operation will result in significant increases in mass losses of the divertor plate (vaporization, sputtering, brittle destruction, and liquid splashing). To predict these losses and potential contamination of the core plasma, two problems must be solved: the dynamics and structure of particles in SOL and 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 the parallel divertor plates, and the SOL plasma becomes collisionless and requires a different treatment than the behavior during normal operation [5]. One main feature of a collisionless SOL plasma is that the edge plasma acts as an electrostatic trap for electrons, since electrons which originally have parallel energy that is lower than the wall potential energy, φ, will be trapped between the inner and outer divertor plates. To obtain the potential φ and corresponding net heat flux of ions and electrons to the divertor plate, we used our previously developed model [6].

III. Particles and energy fluxes during ELMs

The ions escaping the SOL with increased parallel energy due to acceleration in potential φ will have increased velocity and decreased density. The ion particle and heat fluxes leaving the SOL are the same as in the absence of potential. However, the ion heat flux reaching the evolving vapor-cloud above the divertor surface increases due to acceleration in the z-direction as a result of the potential jump [1]. Electrons escape the SOL with a parallel energy $>-e\varphi$. Thus, the average velocity, density n_{ed}, total flux of escaping electrons, and corresponding heat flux are determined by the potential φ. The potential φ is determined by the assumption that fluxes of electrons and ions are equal [1].

IV. Energy and mass balance

It is assumed above that both ions and electrons diffuse across magnetic field lines with an effective diffusion coefficient. The ions freely leave the SOL, escaping electrons freely leave the SOL, and trapped electrons leave the SOL by diffusion in momentum space. Because the energy of these diffusing trapped electrons is near zero, their contribution to the heat fluxes is neglected. The mass and ion energy conservation equations are solved self-consistently [1]. Figure 2 shows the calculated spatial distribution for particle flux, S, electron heat flux, W_e, and ion heat flux, W_i, for the typical tokamak parameters [1].

V. Interaction of incident particles with divertor surface

The integrated HEIGHTS package solves problems related to particle energy deposition, evolution of surface materials, debris formation, vapor radiation magnetohydrodynamics, and erosion physics. This model has been enhanced and used in this analysis. The enhancement includes development of a two-fluid hydrodynamic mixing model, where the incident DT plasma is treated separately from the eroded debris cloud of the divertor materials. We used the forward-reverse radiation transport method for both line and continuum radiation with detail line resolution of the vapor plasma. Parametric studies were completed for different ELM duration (from 0.1 to 1 ms) and different ELM intensity (1-10% Q_o). Two candidate divertor materials were analyzed in this work, beryllium and carbon.

Each flux line that strikes the divertor plate was assumed to have two-dimensional components. Flux lines were distinguished by their distance from the strike point, where the tokamak Separatrix strikes the divertor plate at r = 0. Input parameters were chosen assuming that the SOL width expands 10 times its size at the divertor surface. The effective size of the SOL at the mid-plane was calculated to be 1.975 cm for ions and 0.47 cm for electrons.

For example, for $\eta = 0.1$, the maximum energy density carried by ions at the midplane is 3.6 MW/cm^2, and 0.36 MW/cm^2 at the strike point. For electrons, the maximum energy density is 0.95 MW/cm^2 at the midplane and 0.095 MW/cm^2 at the strike point. The ion energy at the strike point is 12.5 keV and that of the electron is 2.4 keV [1]. Therefore, the ELM model is actually similar to disruption models, but with lower total deposited energy and lower incident particle energy (about 2 keV instead of 10 keV). The density of incoming DT particles stopped in the vapor cloud above the surface is comparable or above the vapor density of the divertor surface. Therefore, the two-fluid mixing model was developed. The front part of the cloud can basically consist of stopped DT particles. All other details concerning models and physics of the plasma-material interaction during a disruption are included in this analysis [7].

Figure 3 shows the Be response to an ELM with different percent Q_o deposited in a duration of 0.1 ms. The erosion from Be vaporization increases significantly with deposited energy >3% Q_o because of the exponential dependence of vaporization rate on surface temperature. At higher ELM energy, more than 90% of the incident energy is absorbed by the vapor cloud and 80% is radiated to nearby areas. Therefore, vapor shielding is also effective during ELMs. The front temperature of the cloud is high, ≈ 25-30 eV, because the cloud front consists mainly of DT ions. The plate surface temperature is high > 3000 K, which results in a high erosion rate because the saturation pressure exceeds the vapor cloud pressure of a few atmospheres. Vapor expansion above the divertor surface also depends on deposited energy.

The important parameter is the net threshold power to the divertor surface, which determines the surface temperature at which the saturation pressure exceeds the cloud pressure of a few atmospheres. The cloud pressure is determined, however, by the DT flux momentum and diffusion across the magnetic field. Because the front of the cloud consists mainly of DT with high conductivity, this condition results in less diffusion and, therefore, higher cloud pressure. For an ELM with $\eta = 0.1$, the Be erosion rate and the expansion of vapor cloud are higher at shorter ELM duration. Beryllium vapor can reach the X-point, which can result in contamination of the core plasma and terminate the plasma in a disruption. Because the temperature of the divertor surface can exceed the threshold for splashing during high-power ELMs, macroscopic losses in the form of liquid droplets can take place. In the case of a well-confined vapor cloud without turbulence, these droplets vaporize by radiation and shield the divertor surface; therefore, the erosion rate will not significantly increase [7]. However, if vapor turbulence exists, the erosion-rate can increase substantially, and plasma contamination/termination becomes a serious problem.

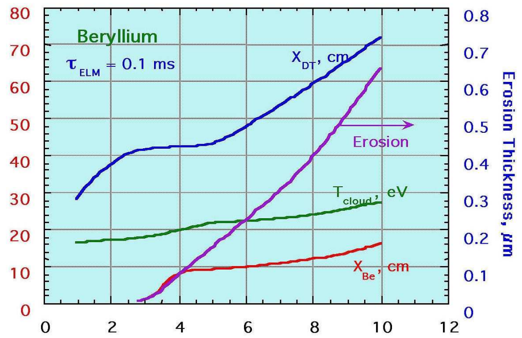

Fig. 3. Beryllium response to an ELM with different % of Qo deposited in 0.1 ms.

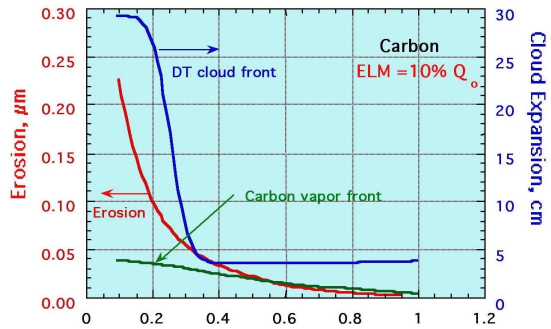

Fig. 4. Carbon plate erosion and vapor expansion as a function of ELM duration for an energy of 10%Qo.

Figure 4 shows the carbon plate erosion and vapor expansion as a function of ELM duration for an energy of 10% Q_o [1]. For $\tau_{ELM} < 0.3$ ms, the erosion rate and the DT cloud front expansion increase significantly, reaching h ≈ 0.25 µm and $X_{DT} \approx 30$ cm at duration $\tau_{ELM} < 0.2$ ms. For an ELM duration of 1 ms, the erosion rate is negligible for ELM energy ≤ 10%$Q_{o.}$ In addition, most cloud volume (80%) is contained by DT, and the carbon vapor expands only to < 5 cm, even for powerful ELMs (10%Q_o) with $\tau_{ELM} = 0.1$ ms. This condition helps reduce core plasma contamination.

VI. Summary

Edge-localized modes may be a serious concern for plasma-facing components during normal operation of the next generation tokamaks. A two-fluid model has been developed to integrate SOL parameters during ELMs with divertor surface evolution (melting, vaporization, vapor cloud dynamics, and macroscopic erosion) using the HEIGHTS numerical simulation package. Initial results indicate an ELM power threshold for each divertor material at which the periodic pulses of energy cause excessive target erosion and large vapor expansion. Large vapor expansion leads to plasma contamination and possible termination in a disruption, even in renewable surface materials such as lithium where erosion is not a problem.

Acknowledgment

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