Extreme Conditions for Plasma-Facing Components in Tokamak Fusion Devices

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***Abstract*—Safe and reliable operation is still one of the major challenges in the development of fusion energy. In magnetic fusion devices, perfect plasma confinement is difficult to achieve. During transient loss of plasma confinement, high plasma power and particle beams (power densities up to hundreds of gigawatts per square meter in time duration on the order of milliseconds) strike the reactor walls, particularly the divertor plate, and can significantly damage the exposed surfaces and also indirectly damage nearby components. To predict the resulting damage of the direct plasma impact on the divertor plate, comprehensive multiphysics multiphase models are developed, integrated, and implemented in the High Energy Interaction with General Heterogeneous Target Systems computer simulation package. The evolution of the divertor material, resulting vaporization, heating and ionization of vapor plasma to higher temperatures, and, consequently, the resulting photon radiation, transport, and deposition around the divertor area are calculated for typical instability parameters of the edge-localized modes and disruption for an ITER-like geometry.**

***Index Terms*—Computer simulation, plasma density, plasma temperature, radiation effects, reactor design, Tokamak devices.**

WE SIMULATED the evolution of an edge-localized mode (ELM) plasma impact onto the divertor surface of an ITER-like geometry with strong and inclined magnetic field configuration using the High Energy Interaction with General Heterogeneous Target Systems (HEIGHTS) computer simulation package with extensive integrated models [1]–[3]. The integrated models included five major parts: Monte Carlo block for plasma particle interaction with solid and plasma matter, magnetohydrodynamic (MHD) block for plasma evolution taking into account magnetic field diffusion, heat conduction and vaporization block for plasma-facing components, heat conduction block for vapor and plasma, and Monte Carlo radiation transport block to calculate detail photon deposition and transport in all phases of target evolution. The modeling was carried out in full 3-D geometry. Fig. 1(a) schematically shows the configuration of the divertor area and the corresponding coordinate system used in HEIGHTS simulation. The current design analysis assumes carbon-based material at the vertical strike points.

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The ELM plasma power impact is simulated in our Monte Carlo algorithm as deuterium–tritium plasma particles flow in the magnetic field along the separatrix line. The spatial distribution of the ELM plasma impact is modeled exponentially along the strike point with a maximum power deposition of 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 ($\sim$10% of the pedestal energy) [4].

We studied the effect of ELMs on the divertor plate with different durations of 1, 0.5, and 0.1 ms. The ELM durations of 0.5 and 1 ms correspond to deposition powers of 0.92 MW/cm^2 and 0.46 MW/cm^2, respectively. The shorter ELM initiates intense surface vaporization. The produced plasma cloud has a high temperature (up to 60 eV) and is very effective in forming a stable vapor/plasma shielding for the ELM incoming particles because of the insufficient time for vapor MHD motion and expansion/transport. The plasma shielding layer acts as an absorption layer for the rest of the ELM impact near the strike point location. The ELM particles decelerate, scatter, and deviate from the initial impinging direction in the plasma cloud that results in a significant decrease in 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 relatively in confined position, the processes of plasma radiation and transport are evolved in this confined area around the divertor strike point but relatively far from nearby components. The impact ELM energy is consumed mostly for vaporization because of insufficient time for thermal relaxation and heat conduction inside the divertor plate.

The MHD role and the expansion of the evolved vapor plasma increase appreciably with ELM impact duration. The plasma cloud has sufficient time for motion and expansion in the dome area [see Fig. 1(b)]. The effectiveness of plasma shielding is then reduced, and the erosion area is more confined closer to the strike point with deeper erosion at this location. The process of plasma cloud radiation is combined with the appreciable MHD vapor plasma motion in this case, and it redirects the ELM impact energy from the strike point area and decelerates divertor erosion; however, it increases the risk of nearby component damage. Fig. 1(c) shows the spatial distribution of radiation fluxes in the divertor area for the longer ELM impact of 1.0 ms.

We calculated the incident photon fluxes along the dump and dome surfaces using our Monte Carlo radiation transport model implemented in HEIGHTS. 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

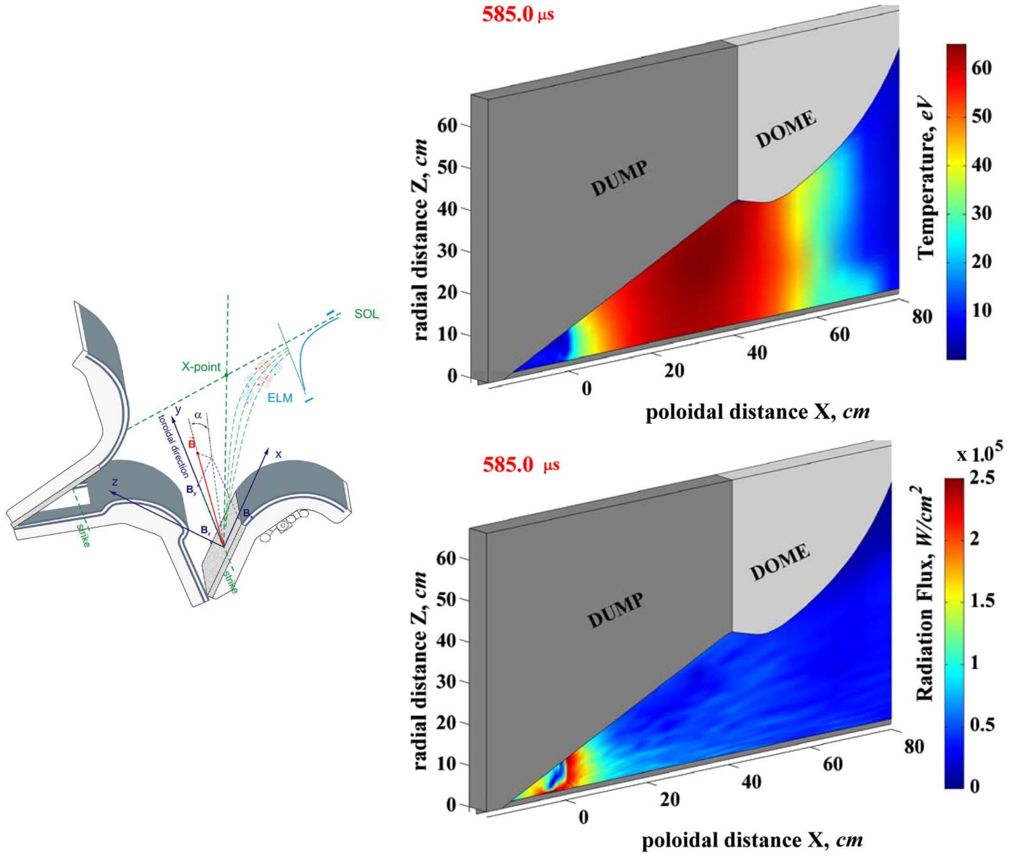

Fig. 1. (a) Schematic illustration of ITER-like divertor design and coordinate systems used in HEIGHTS modeling (left). (b) Evolution of carbon plasma temperature from the divertor plate during an ELM of 1-ms duration (top). (c) Distribution of radiation fluxes in the divertor area during an ELM of 1-ms duration (bottom).

smaller but in the same order as the direct plasma energy depositions. The heat load at nearby divertor components increases considerably for the disruption case, i.e., total loss of all plasma energy, which corresponds to a higher direct energy deposited on the divertor plate [3].

The net erosion damage profile strongly depends on both the impact energy and duration that are sufficient for surface vaporization and plasma cloud formation. The bulk target thermal relaxation due to heat conduction inside the divertor plate slightly helps in mitigating divertor erosion because of the diffused energy inflow, particularly at longer durations.

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