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Cryogenic Pellet Ablation Physics and Integrated Modelling of Shattered Pellet Injection

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While experimental dependence of the pellet penetration depth can be approximated using simple scaling laws, underlying physics is extremely complex and requires challenges for multiscale and multiphysics modelling. The electron density of an ablation cloud changes over eight orders of magnitude from solid density (10^{28} m^{-3}) to background one (10^{20} m^{-3}) as it expands along the magnetic field line. Because the ablation cloud is over-pressured by heating from hot ambient electrons, the materials can drift down the magnetic field gradient during assimilation. For Shattered Pellet Injection (SPI), the situation is further complicated by that many fragments simultaneously penetrate into core plasma, and massively injected materials trigger global instabilities and thermal quenches. Although we have not yet acquired the SPI simulations that can consider all the relevant mechanisms self-consistently, our understanding has made a constant progress through the ITER DMS design validation activities.

In ITER, hydrogen and neon pellets will be used to fulfill the requirements for disruption mitigation. For Massive Gas Injection (MGI), it has been widely acknowledged that a radiative cold front is formed in the peripheral region, which destabilizes tearing modes and triggers a thermal quench. While the formation of the radiative cold front is followed by gas penetration during MGI, solid shards can precede it in the case of SPI and fuel particles in the core region. Runaway Electron (RE) avoidance may require rising the electron density by a factor of 20-40 or more. Therefore, a guideline for optimizing the SPI parameters is to raise the core density by the arrival of pellet shards at the plasma center before the trigger of a thermal quench. While larger fragment size, higher injection velocity, and higher velocity dispersion support this trend for one-stage neon mixed pellet injection, the same idea motivates us staggered injection of pure H_2 and neon mixed pellets for the avoidance of hot-tail RE mechanism. However, recent observations show that a poor assimilation efficiency of pure H_2 SPI poses a trade-off. When comparing the non-shattered pellet injection between different compositions, although the penetration depths are comparable between pure H_2 and 5 % neon mixed pellets, the density rise at the ablation position is only observed for the neon mixed pellets; in contrast, the pure H_2 injection exhibits a hollow density profile and particle loss to the scrape-off layer. The observation is explained by the dependence of the ExB drift displacement on the ablation cloud pressure, and less radiative pure hydrogen pellets lead to the poor assimilation efficiency, as observed for pure D_2 SPI at DIII-D. Taking such dependence of the ExB drift displacement into account, major trends of the ITER DMS functions have been analyzed for variations of thermal energy content, electron temperature, and magnetic field strengths through staged upgrade of the plasma performance of an ITER pulse using the 1D integrated disruption code INDEX.

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