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Impurity Mixing in Massive-Gas-Injection Simulations of DIII-D TH-S

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NIMROD MHD modeling of massive gas injection elucidates how both 2D and 3D flows, particularly those associated with the m=1/n=1 instability, determine impurity mixing efficiency during massive gas injection (MGI) in various configurations. MGI experiments have the aim of mitigating potentially damaging disruption effects, including heat loads and wall forces, while also increasing the total electron density toward the goal of collisional suppression of runaway electrons (REs). These simulations provide insight into the optimal configuration for achieving high core electron density with MGI. Since high-pressure gas jets do not penetrate deeply into high-performance tokamaks, a large increase in the core electron density requires impurity mixing by flows associated with macroscopic MHD turbulence during the thermal quench (TQ) phase of the disruption. To understand and optimize these effects, MHD modeling which includes an impurity species is a useful tool. Previously, impurity mixing results were reported for a simulation of Alcator C-Mod with edge peaked impurity injection [1], in which it was noted that phases of rapid increase in core impurity density were simultaneous with the saturation of 1/1 modes, but did not appear concurrent with higher m or n modes. In that simulation, the impurity injection profile was both poloidally and toroidally symmetric for simplicity, but the edge impurity distribution — and possibly the effects of mixing — will be more localized in the case of a real gas jet.

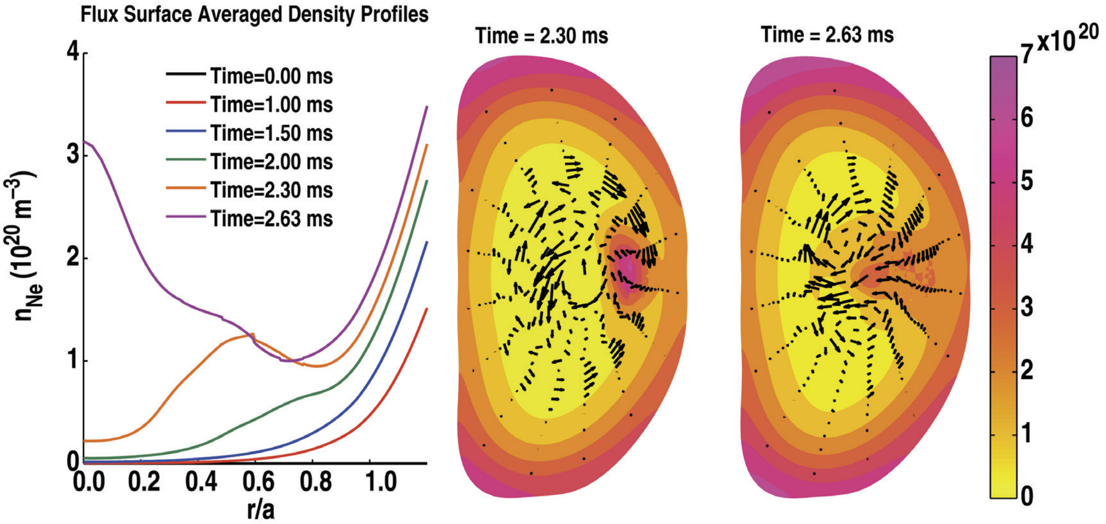

Fig. 1. (a) Flux surface averaged neon density profiles at six times in the simulation, where the plasma contains no Ne at t=0 and neutrals are continuously injected into the edge. (b) Contours of neon density at ϕ=0 for the last two times shown at left. Arrows indicate direction and relative magnitude of poloidal velocity.

Here we present simulations of DIII-D in which neon impurity atoms have been injected primarily into the edge to initiate a thermal quench. In the initial simulation, the impurity source is poloidally and toroidally symmetric, but more strongly localized to the edge than in the C-Mod simulation. We examine in closer detail the 2D and 3D flows responsible for the sudden increase in core density at the time of the 1/1 mode saturation, which is also responsible for the final drop in core T_e that concludes the TQ phase. Figure 1 shows the evolution of the total neon density in a DIII-D simulation in which the edge neon density is gradually increased as it diffuses and mixes into the core. The flux surface averaged profiles show a sudden rapid increase in core Ne density between 2.30 and 2.63 ms, which corresponds to the time of the 1/1 mode saturation in this simulation. Although the neon source term is poloidally symmetric, the neon distribution does not remain poloidally symmetric, which can be seen from the Ne density contour plot at 2.30 ms. A poloidally localized blob forms on the low-field side, just outboard of the magnetic axis, due to the 2D poloidal flow pattern indicated by the arrows in the figure. A core localized 3D flow pattern with n=1 symmetry then appears and pulls the impurity blob into the core by 2.63 ms.

The 2D and 3D aspects of impurity assimilation seen in the symmetric impurity injection simulation raise interesting questions about the effects of non-symmetric impurity sources on MHD mixing results. NIMROD can be run with both poloidally and toroidally asymmetric sources. First, n=0 but poloidally asymmetric Ne sources are used to simulate DIII-D mitigated disruptions with impurities injected only on the high-field side, then only on the low-field side (keeping the total rate of impurity injection constant). Thus, we obtain a direct comparison of the core Ne density versus time for the three poloidal symmetries. We find that the MHD onset time following the initial edge-cooling phase remains approximately unchanged for each impurity injection profile. Contours of ionized neon density from the early phase of a high-field side injection case are show in Fig. 2. Although the impurities are injected as neutrals mainly in the vacuum region, the Ne can be seen to ionize approximately as it reaches the separatrix.

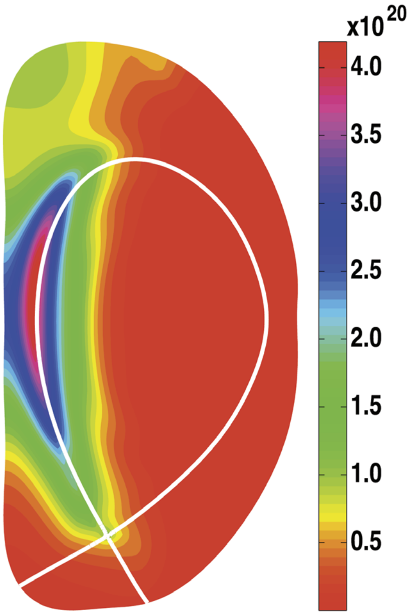

Fig. 2. Contours of ionized Ne density shortly after the start of high-field-side injection.

The final set of simulations compare impurity assimilation for toroidally symmetric and asymmetric sources. Although real gas jets are highly toroidally localized, the source localization is limited by toroidal resolution of the simulations, which include toroidal mode numbers n=0-10. Furthermore, the initial spreading of the dense neutral jet cannot be appropriately modeled by fluid equations, thus the simulation is initiated assuming the impurities have already spread a significant distance around the torus. From this point, fast parallel heat transport into the high impurity density region maintains approximate toroidal symmetry of the electron temperature, and thus the higher pressure in the impurity jet drives toroidal expansion of the plume. The simulations are not expected to capture every aspect of an MGI rapid shutdown, but serve as numerical experiments to understand the effects of impurity source location and localization on assimilation, and thus help to optimize MGI for disruption mitigation and runaway electron suppression.

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[1] V.A. Izzo, *et al.*, Nucl. Fusion **51** (2011) 063032.