Contribution ID: **19** Type: **Contributed Oral**

Parallel transport induced tokamak thermal quench and its mitigation

Tuesday, 19 July 2022 11:35 (25 minutes)

Thermal quench (TQ) marks the point of no return in a tokamak disruption. It not only brings a thermal load management issue at the divertor plates and first wall, but also determines the runaway seeding for the subsequent current quench (CQ). There are two ways to trigger a TQ, one is the globally stochastic magnetic field lines that connect the hot core plasma to the cold boundary, while the other is high-Z impurity injection. In both situations, a nearly collisionless plasma is made to intercept a radiative cooling mass (RCM), being that an ablated pellet or a vapor-shielded wall. Previous JET experiments and more recent DIII-D data have demonstrated a wide range of TQ durations with and without high-Z pellet injection, which is concerning for future tokamak reactor operations.

With fully kinetic VPIC simulations and analytical theory, we have uncovered three underlying parallel transport mechanisms that govern the thermal collapse of a fusion-grade and hence nearly collisionless plasma. They are: (1) thermal collapse of surrounding plasmas due to a localized RCM is dominated by convective energy transport as opposed to conductive energy transport, and as the result, TQ comes in the form of four propagating fronts with distinct characteristic speeds, all originated from the RCM, and core thermal collapse is a lot slower than one would expect based on electron thermal conduction of Braginskii or free-streaming; (2) cooling of perpendicular electron temperature closely follows that of parallel electron temperature, and in a nearly collisionless plasma, is mostly driven by fast electromagnetic kinetic instabilities of two kinds, sequentially in time; (3) the overall TQ inevitably has a transition from the collisionless phase to the collisional phase, the duration of which have distinct physics scalings, and the two of which are sandwiched by a transition period of its own unique physics scaling. Altogether, we can now predict the TQ history of a plasma at given density and temperature as a function of the magnetic connection length.

These physics advances inform the strategies for avoiding and mitigating the deleterious effects of TQ on both thermal load management and the subsequent Ohmic-to-runaway current conversion. In the ITER scenario of high-Z pellet injection for spreading plasma heat load via radiation, pellet assimilation and spatial homogenization are both tied to the TQ physics. The staged pellet injection suffers particularly strong constraints that result in severe performance degradation. In situations where runaway avoidance is a priority, one can no longer rely on impurity radiation for thermal load management. The drastically different TQ durations in the collisionless and collisional regimes point to the alternative mitigation approach that relies on dilutional cooling via massive hydrogen injection to place the entire TQ in the collisional phase, in which case the CQ and TQ span the same period. If there is not enough lead time for predisruption pellet injection, the physics insights place stringent constraints on what an optimal passive mitigation method would entail, especially when runaway avoidance is also a consideration.

Work supported by U.S. DOE OFES and OASCR.

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Session Classification: Disruption Consequences

Track Classification: Consequences