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DIII-D research in support of the ITER disruption mitigation system

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Introduction - A reliable and effective disruption mitigation system (DMS) will be critical to ITER and any future burning plasma tokamak. Pioneering studies on DIII-D examine the physics and limitations of shattered pellet injection (SPI, the baseline ITER DMS technology), probe the mechanics of runaway electron (RE) evolution, and are developing a new mitigation technology to provide "inside-out" mitigation through core impurity deposition. These efforts directly support the development and operation of the ITER DMS [1].

Shattered Pellet Injection - Recent experiments on DIII-D [2] examined the superposition of two toroidally separated SPI (Figure 1a). The ability to additively superimpose numerous SPI prior to the thermal quench has become a critical question for ITER, as recent modelling [3] casts doubt on the ability to dissipate an existing ITER runaway plateau in a technically feasible manner. In response, focus has turned to runaway seed suppression, requiring large quantities of deuterium injected from multiple SPI prior to the thermal quench [4]. In the experiment, it is found that radiation fractions near the injector ports follow the expected behavior for a low Ne quantity pellet (10 torr-L) and a pure Ne pellet (400 torr-L). However, the radiation fraction is reduced (Figure 1b), the current quench duration increases, and the plasma cooling duration decreased relative to a single 400 torr-L pellet when two pellets reach the plasma edge simultaneously, indicating a degradation in the effectiveness of mitigation.

Two hypotheses are proposed for this degradation in performance during simultaneous injection. The simplest is that the less massive, higher velocity mixed species pellet reaches the q=2 surface before the pure Ne pellet even when both "simultaneously" reach the plasma boundary. Thus the mixed pellet dominates the mitigation process unless the more massive, slower pure pellet reaches the edge significantly earlier. However, this simple picture is not consistent with the observed reduction in cooling duration during simultaneous injection. Alternately, the presence of impurities on multiple flux tubes when the pellets arrive simultaneously may induce global MHD more rapidly than a single flux tube of impurities, leading to reduced cooling duration and subsequently less impurity assimilation. Experiments using two pure Ne pellets of equal mass are planned to test these hypotheses.

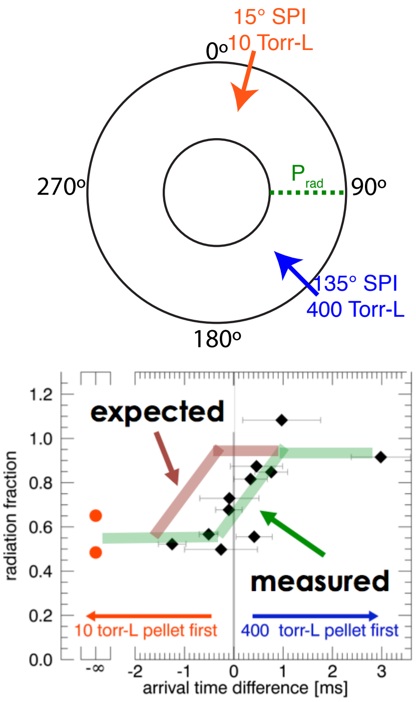

Figure 1: a) Plan view of DIII-D SPI and fast bolometry locations. b) Superposition of toroidally separated SPI with small (10 torr-L) and large (400 torr-L) quantities of neon with differing time delays.

Runaway Electrons - The novel tangentially viewing Gamma Ray Imager (GRI) [5] enables examination of the RE energy distribution function evolution in the flattop of low-density, Ohmically driven quiescent discharges using MeV-scale bremsstrahlung emission to provide direct comparison to theoretical models of RE dissipation [6,7]. The observed energy spectra display a non-monotonic energy "bump", indicating the energy attractor predicted by theory [8], as well as the motion of the bump in energy space as the collisionality (density) is varied (Figure 2). Measured spectra also exhibit a strong dependence of the high-energy tail upon the synchrotron force (varied using Bt) in qualitative agreement with theory. The energy spectra are significantly narrower in experiment than model, perhaps indicative of the influence of kinetic instabilities upon the high-energy RE [9]. The RE dissipation rates are found to be energy dependent, with high-energy RE crossing from growth to dissipation near predicted values of E/E_{crit}, but the crossing point of lower energy RE exhibiting anomalously large dissipation rates compared to predictions.

Development of Core Impurity Deposition - Recent modeling [10] indicates that core impurity deposition, wherein the injected radiating impurities cool the plasma core without significantly cooling the edge, shows promise to dramatically improve all stages of the disruption mitigation process over conventional edge-cooling methods (e.g., MGI or SPI). Core radiation inverts the TQ process, cooling from the inside-out and minimizing heat transport to the scrape-off layer to protect the divertor. High impurity assimilation due to deposition in the core enables the use of low-Z impurities (e.g. beryllium dust) to achieve high thermal radiation fraction while still providing a warm CQ with acceptably slow current decay rate to avoid mechanical damage from eddy currents. In addition, inside-out mitigation is predicted to create stochastic regions throughout the entire cross-section of the plasma during the TQ that can rapidly de-confine RE seeds and provide high core densities to suppress RE seed formation and avalanche multiplication.

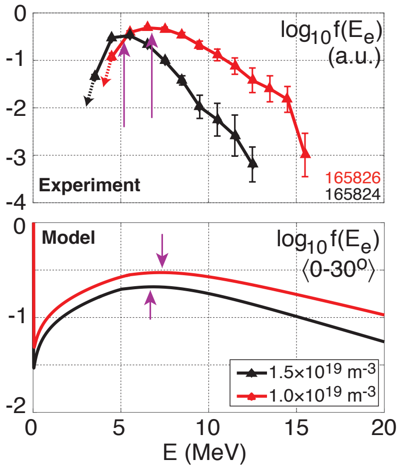

Figure 2: Comparison of experimental (top) to modeled (bottom) RE energy distributions for two QRE discharges of varying collisionality. Arrows indicate

Experiments injecting boron-filled diamond shell pellets into the DIII-D tokamak provide the first demonstration of disruption mitigation through core impurity deposition. The shell pellet technique utilizes a thin, minimally-perturbative shell to transport the enclosed radiating impurity (boron dust) to the plasma core before dispersal, delaying the onset of global MHD that is typically initiated by conventional edge-cooling techniques (e.g. massive gas injection). Visible imaging shows the shell ablating gradually until the boron is released near the magnetic axis (Figure 3). 0-D mitigation metrics generally improve with injection velocity, indicative of the

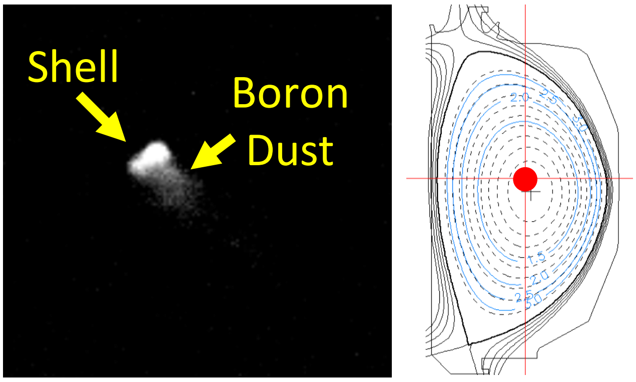

Figure 3: a) B-II imaging showing first dispersal of boron powder from ablating shell. b) Location of pellet at point of initial boron dispersal, assuming no toroidal deflection of pellet trajectory.

importance of deep deposition. Density measurements account for a large fraction of electrons provided by the pellets, indicating high impurity assimilation fraction. Future work and the design of ITER-relevant shells are discussed.

Conclusions - The DIII-D program continues to pursue a vigorous disruption mitigation program focused on supporting the development of the ITER DMS. For several years DIII-D has been the only device with an operational SPI system, but new systems coming online in 2018 at JET and J-TEXT, as well as planned systems elsewhere, will enable this research to expand to international collaboration and comparison. DIII-D continues to improve its runaway electron diagnostic capability to provide the close theory-experiment coupling that is necessary to solve the runaway electron problem for ITER. Moving forward, the program will continue development of novel disruption mitigation techniques that may offer improved performance compared to the baseline ITER SPI system.

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