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Experiments on Disruption Runaway Electron Suppression in the DIII-D Tokamak

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Localized wall damage from runaway electrons formed during tokamak disruptions is a serious concern for future large tokamaks like ITER. In the DIII-D tokamak, a large variety of experiments have been conducted to understand runaway electron formation, amplification, and loss; and to devise methods for avoiding wall damage due to runaway electrons following disruptions. The experiments can be broken into two categories: massive impurity injection experiments and runaway electron studies.

In massive impurity injection experiments, attempts are made to achieve very high total electron density ($n_{crit} \approx 5 \times 10^{16}$ cm^{-3}) during the current quench to collisionally suppress any possible runaway electron seeds. Massive gas injection (MGI) experiments indicate that the limiting factors in impurity assimilation are the limited mixing efficiency of the plasma (~20% during the thermal quench and ~1% during the current quench) as well as the limited rise time of the gas injection impurity delivery relative to the thermal quench (TQ) onset time. Present modeling of MGI in ITER based on DIII-D mixing efficiencies suggests that MGI will work well in ITER for heat load and vessel force mitigation, but may not collisionally suppress runaway electrons, suggesting the need for investigating alternate impurity delivery methods. First efforts at improving assimilation over that achieved with MGI have been made using either shattered pellets or shell pellets. Shattered D_2 pellets, consisting of a stream of D_2 ice shards, have shown record-level localized electron densities at the injection port; however, the toroidally averaged mid current-quench densities are not much larger than best-case MGI experiments (total electron density $n_{tot} \approx 0.2 n_{crit}$ achieved with simultaneous five-valve He MGI), suggesting that particle confinement during the CQ may be limiting the achievable assimilation. Shell pellets consist of a dispersive (powder) payload held together by a thin plastic shell which acts as a sacrificial ablator. Preliminary experiments at demonstrating the shell pellet concept were successful with small (OD ~ 1 mm) shell pellets. Large (OD ~ 1 cm) shell pellets with a t = 1 mm polystyrene shell passed through the core without releasing their payload, indicating that the plastic shell ablation rate was slower than expected for large shell pellets, possibly due to anomalous rapid heat transport in the strongly perturbed plasma. The capability to launch large shell pellets with a thinner t = 0.1 mm shell is presently under development.

Normally, runaway electron (RE) formation is quite small in DIII-D disruptions and MGI shutdowns. To study RE formation, control, and dissipation, we intentionally create large (>10 kA) RE seeds by shutting down high temperature target plasmas with small (D = 2.7 mm) cryogenic argon pellet injection. Typically, the initial RE seeds appear to be largely lost to the vessel wall during the TQ MHD. Consistent with NIMROD simulations of TQ MHD mode structure, this prompt TQ loss of RE seeds is observed to be much larger in lower single null plasma discharges than in inner wall limited discharges. Attempts to intentionally enhance the RE prompt loss using externally applied non-axisymmetric magnetic field errors have not shown a clear effect yet.

In some cases, sufficient RE seeds survive the prompt loss phase to amplify by electron avalanche during the CQ and form a high current (0.1–0.5 MA), long-lived (>100 ms) RE beam whose current is carried almost completely by the REs. RE avalanche gains in DIII-D appear to be of order $50\times$, consistent with theory expectations.

Preliminary experiments at controlling these RE beam currents with external coils have shown clear ability to move the RE beam vertically and hold the

RE beam vertically stable. Reliable radial control has been more difficult to achieve, due to the configuration of the DIII-D shaping coils, although radial motion of the beam in response to control input has been demonstrated. Additionally, ohmic current coil ramps have been used to ramp the runaway current up and down, demonstrating the possibility of dissipating RE energy harmlessly into external coils. Typically, the RE beam is lost suddenly to the wall in a final loss instability before complete ramp down to zero RE current is achieved. The cause of this final loss instability is not understood at present. In several instances, however, a complete ramp down to zero current without final loss instability has been achieved.

The RE beam plasmas actually consist of two components: a cold ($T \approx 1.6$ eV), dense ($n_e \approx 5$–$15\text{x}10^{13}$ cm^{-3}) background plasma co-existing with the very energetic ($T_e \approx 20$ MeV), tenuous ($n_R \approx 4$–$18\text{x}10^{9}$ cm^{-3}) RE beam. Collisional drag on the REs in these experiments is thought to be dominantly due to high-Z impurities in the plasma. Normally, the RE plasmas contain of order ~20% argon ions from the argon pellet; however, this high-Z impurity content and resulting RE collisional dissipation can be increased by additional injection of high-Z gas such as Ne, Ar, or Xe. Comparisons of the RE plateau composition with expected collisional dissipation rates suggest the presence of an anomalous loss of runaways to the wall at a rate of ~10/s, possibly due to drift orbit losses.

Preliminary measurements of the energy balance during the final loss of RE beams striking the DIII-D wall have been performed. These studies indicate quite different dynamics for fast RE-wall strikes (with interaction times $<< \tau_{wall} \approx 8$ ms where τ_{wall} is the vessel wall time) compared with slow RE-wall strikes (with interaction times $>> \tau_{wall}$). In slow RE-wall strikes, a significant fraction of the RE beam magnetic energy may be converted into RE kinetic energy. In fast RE-wall strikes, the RE beam magnetic energy appears to be dominantly lost by conversion into ohmic (cold) plasma current and wall currents.

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