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Control and Dissipation of Runaway Electron Beams Created During Rapid Shutdown Experiments in DIII-D* EX-S

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Improvements in runaway electron (RE) beam control during rapid current shutdowns in DIII-D have led to several important results and insights on RE control and dissipation for ITER including controlled ramp-down of RE beam to zero current and use of injected high-Z impurities to control RE dissipation. RE dissipation rates appear larger than predicted by electron collisional drag, indicating that pitch angle scattering cannot be neglected in RE dissipation. These studies are critical for ITER where high-current (multi-MA) RE beams may form and be lost to the wall, causing significant damage to the plasma facing components.

In DIII-D, improvements in RE beam control have enabled stable confinement of RE beams out to the volt-second limit of the ohmic solenoid. In the experiments, high-current ($I_p \approx 300$ kA) RE beams are formed using 2.7 mm (8 torr-l) cryogenic argon pellet injection. Immediately after the current quench, an open loop outward push from plasma shaping coils is used to avoid erratic feedback and loss of the RE beam into the center post. Subsequently, robust linear position estimators are enabled to allow vertical control of the RE beam position. With vertical position control of the RE beam established, ohmic coil feedback control of the RE beam current has been achieved, as shown in Fig. 1(a), where different RE beams are either held at constant current for 600 ms (blue), or held for 200 ms and then ramped down (red), or immediately ramped down to nearly zero current (black) [1].

Increased dissipation of RE beam current has been demonstrated by massive gas injection (MGI) of high-Z impurities into RE beams. This is illustrated in Fig. 1(b) for argon and neon MGI.

Comparison of the measured RE current growth/decay rates with avalanche theory indicates the presence of an anomalous current loss at a rate of order $\dot{I}_p / I_p \approx -10/\text{s}$. The composition (e.g.

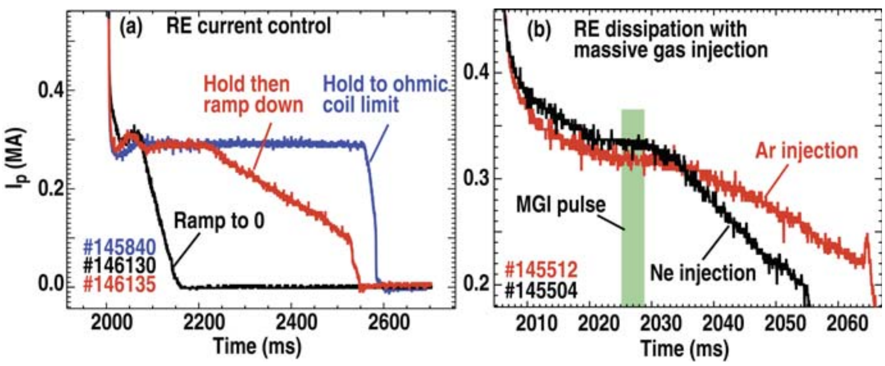

Fig. 1. (a) Runaway electron beam current control showing: shot with constant current out to ohmic coil limit, shot held for 200 ms then ramped down, and shot immediately ramped down to zero current; (b) Dissipation of runaway electron beam current following massive gas injection of 320 Torr-l argon or 1050 Torr-l neon.

argon ion content) of the RE beams can measured spectroscopically. From the composition of the RE beam, the expected collisional decay rate of the RE beam current can be estimated from avalanche theory [2]. Figure 2(a) shows the measured and predicted RE current decay rate for ohmic coil ramps of the RE beam current [3].

The anomalous loss of RE current seen in Fig. 2(a) appears to be related to the density of high-Z impurities in the plasma. This is shown in Fig. 2(b), where the measured current decay rate following massive gas injection (MGI) into RE beams is shown. It can be seen that the anomalous loss grows larger with increasing high-Z impurities (neon or argon), but grows smaller if a large quantity of low-Z impurities (deuterium or helium) is injected.

The importance of high-Z impurities in causing anomalous RE loss suggests that pitch-angle scattering off high-Z nuclei may play a role; this is typically ignored in favor of electron-electron collisions. Pitch-angle scattering could cause increased diffusion of REs into the wall, thus causing anomalous loss; this is supported by diagnostic pellet experiments which reveal the presence of diffuse REs far outside the main beam [4]. Alternately, an increased collisional slowing of fast electrons could be occurring. Evidence of this is seen in the measured distribution function, Fig. 2(c), which indicates that the fast electron distribution is much more weighted toward low energies than expected from avalanche theory.

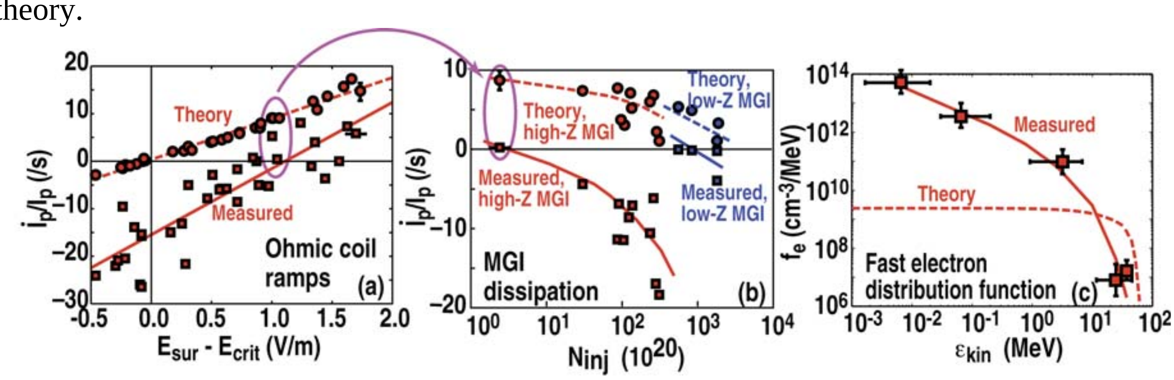

Fig. 2. (a) Measured runaway current decay rate as a function of toroidal surface electric field minus critical field for avalanche during ohmic coil ramp experiments. Baseline case with no current ramp is circled. (b) Measured runaway current decay rate after massive impurity gas injection into runaway beam. (c) Fast electron energy distribution function as a function of electron kinetic energy measured for baseline case.

In addition to experiments on controlled dissipation of RE beams, data has been gathered on undesirable rapid (uncontrolled) RE-wall strikes. Uncontrolled loss is observed to proceed rapidly once the RE beam (minor radius a≈0.2 m) touches the vessel wall. Strong toroidal asymmetries in the resulting kinetic energy deposition are observed [5]. An increase in peak RE kinetic energy is observed as the RE beam moves into the wall, presumably due to increasing loop voltage in the RE beam. If the RE beam moves into the wall on a timescale slow compared with the conducting wall time (τ_{wall}≈8 ms), the resulting increase in total RE beam kinetic energy can be large (up to 10 ×), possibly due to conversion of magnetic to kinetic energy, as has been observed in JET [6]. If the RE beam moves into the wall on a timescale short compared with τ_{wall}, RE current appears to be largely converted into wall currents and ohmic plasma current. This result is encouraging for ITER, which will have a long wall time τ_{wall}≈600 ms, presumably longer than typical RE-wall strike timescales.

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