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GENERAL ATOMICS

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Impact of Core Modes, Islands, and Instabilities on Runaway Electron Confinement

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Fast visible-NIR imaging of synchrotron emission from runaway electrons (RE) has been used in DIII-D [1] to study the generation, transport, and confinement of runaway electrons. Analysis of the synchrotron emission (SE) from runaway electrons with energies ≥25 MeV indicates that RE confinement is strongly affected by core islands, active MHD modes, and velocity space anisotropy-driven kinetic instabilities. In next-step tokamaks, such as ITER, large toroidal electric fields can be produced in un-mitigated disruptions or rapid shutdowns to mitigate disruption damage that would produce multi-megamps of REs with energies ≤100 MeV. Understanding the production, confinement, and loss of these highly relativistic electrons is an ITER urgent need since they could damage the first wall. REs have been studied in DIII-D in two distinct classes of discharges: trace levels (~kA) of RE current produced by secondary avalanche acceleration of primary (Dreicer) seeds in steady-state (5 s), quiescent ohmic discharges with several hundred kA of thermal plasma current [2]; and long-lived (up to 0.5 s) plateaus of hundreds of kA of RE current following the current quench of discharges terminated with the injection of argon cryogenic pellets [3,4].

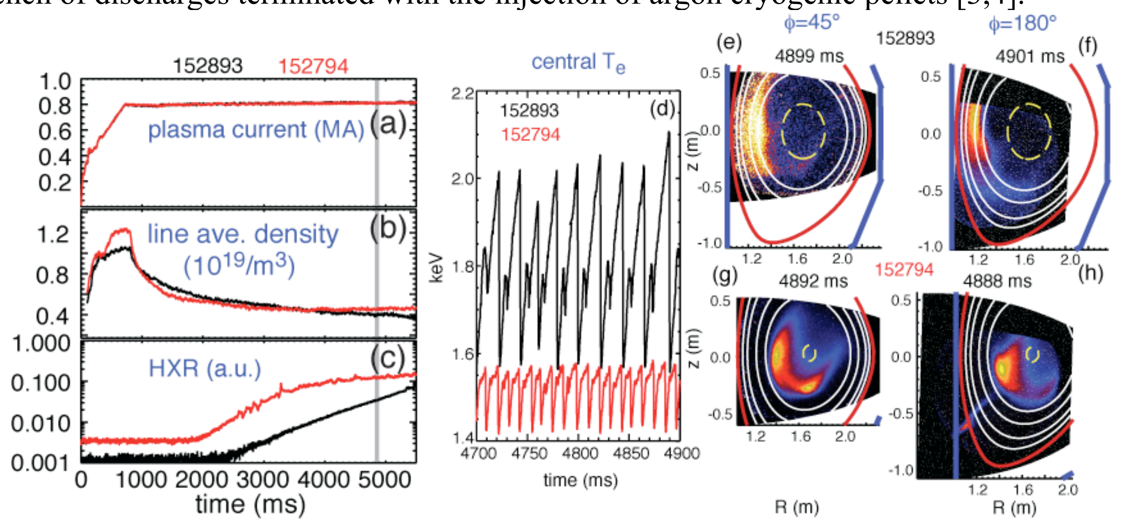

Fig. 1. Evolution of (a) plasma current I_p, (b) line average density, and (c) hard x-ray signal HXR in quiescent runaway electron (QRE) discharges without (black) and with (red) an early locked mode. The grey vertical line indicates the time of the synchrotron emission images in (e) through (h). (d) Sawteeth in the electron temperature T_e on the magnetic axis, for the same 2 QRE discharges. Synchrotron emission (SE) at (e,g) 45° and (f,h) 180° toroidally for the 2 QRE discharges in (a–d), indicating the axisymmetric structure of the emission crescent toroidally. The vacuum vessel, separatrix, q=1.5, 2, 2.5, and 3 surfaces, and the sawtooth inversion radii are indicated by the blue, red, white, and dashed yellow lines respectively.

Quiescent runaway electron (QRE) discharges are produced in DIII-D by allowing the plasma density [Fig. 1(b)] to decay following the plasma current I_p ramp [Fig. 1(a)]. As the density decays, trace levels of REs are accelerated, leading to increased hard x-ray emission [Fig. 1(c)]. The synchrotron emission (SE) pattern from REs with energies ≥ 25 MeV is crescent shaped, centered between the q=3/2 and q=3 surfaces [Fig. 1(e,f)] for discharges with significant sawteeth and without an early locked mode [black traces, Fig. 1(a–d)]. This crescent shape illustrates a strong high field/low field side asymmetry in the SE intensity, which is qualitatively consistent with the strong velocity pitch angle dependence of the SE, and conservation of the adiabatic invariant. The hollow core in the SE pattern shrinks significantly [Fig. 1(g,h)] in a QRE discharge with an early locked mode [red traces, Fig. 1(a–d)], suggesting that the sawteeth [Fig. 1(d)] transport REs to larger minor radius. Trapping and confinement of REs is also seen within slowly rotating 2/1 islands after error field penetration events in these discharges.

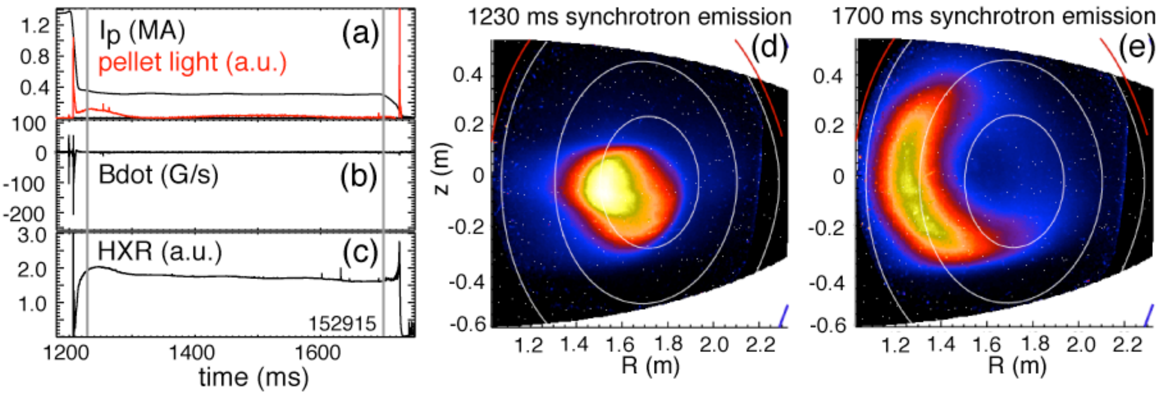

Fig. 2. Evolution of (a) I_p and light emitted by argon pellet, (b) magnetic fluctuations, and (c) hard x-ray emission HXR for a discharge terminated with an argon pellet at 1200 ms that develops a 0.55 s runaway electron plateau of 350 kA. SE from (d) 1230 ms (left grey line), and (e) 500 ms (right grey line) in the plateau. In (d) and (e), the blue and red lines are the vacuum vessel and separatrix. The white contours are the locations of the q=1, 2, and 3 surfaces just *before* the argon pellet is injected into the plasma.

RE plateaus with 300-500 kA of RE current for up to 0.5 s are generated in DIII-D by rapid discharge termination with argon cryogenic ("killer") pellets, as shown in Fig. 2(a) through (c). The argon pellet in injected at 1200 ms, as indicated by the burst in visible light from the pellet [red trace in Fig. 2(a)] and induced MHD activity, as indicated by the magnetic fluctuations [Bdot, Fig. 2(b)]. The RE synchrotron emission pattern early in the post-current quench plateau at 1230 ms [left vertical grey line in Fig. 2(a–c)] has the expected tilted ellipse shape [Fig. 2(d)] due to the field line pitch and the finite velocity pitch angle $\varepsilon = v_\perp / v_\parallel \sim 0.1$. However, the SE pattern develops into a pronounced crescent shape during the plateau [Fig. 2(e)], indicating that at least some of the physics leading to these non-elliptical SE patterns seen here and in the QRE discharges is generic, and not specific to either QRE or RE plateau conditions. This crescent pattern can be steady for long periods of time (≤0.5 second), but in some cases, the crescent pattern relaxes rapidly (within <50 μs) into an ellipse correlated with a burst of gamma rays, indicating rapid loss of RE confinement to the vessel walls. This behavior is suggestive of a velocity space anisotropy-driven instability which might be a problem for controlled dissipation of RE plateaus following disruption mitigation in ITER.

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