Primary runaway electron generation and saturation in a tokamak

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Understanding the physics of runaway electrons (RE) is essential for mitigating the most deleterious effect of tokamak disruptions. RE population is generally thought to come from a two-step process: 1) primary REs are pulled from the bulk population and accelerated to relativistic energy by the parallel electric field; 2) primary REs knock low-energy electrons directly into the runaway regime via large-angle scatterings (avalanche).

We show that the synchrotron radiation (SR) due to toroidal motion and Brehmstrahlung radiation not only set an accumulation point in RE energy space, but also enable the formation of a saturated primary RE population. Electrons accumulate around p_{max} where all drag forces balance the parallel electric field acceleration. The saturation is then achieved due to a global circulating flow pattern in the $(p, \xi \equiv p_{\|}/p)$ space. As the REs are stuck at p_{max}, pitch-angle scattering turn them away from $\xi = 1$ so that the SR due to gyration becomes enhanced eventually, leading to a phase-space return flow toward lower p and ξ. This global circulation in phase-space reaches a steady state and produces a saturated primary RE population, which appears as a bump in the (p, ξ) space as opposed to an attractor at its absence. Our new and comprehensive findings are readily appreciated in the context of previous and contemporary work [1].

Finally we note that the toroidal geometry introduces separate trapped and passing regions in (p, ξ) space. The trapped electrons can no longer experience parallel electric field acceleration, so the phase-space flow is significantly modified. As the result, magnetic trapping can modify the threshold electric field (increase), the energy range and size of the primary RE population via changing the global circulating pattern.

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[1] J. Martin-Solis et. al., POP (1998); P. Aleynikov, PRL (2015); A. Stahl, PRL (2015); J. Decker, PPCF (2016)