Production and damping of runaway electrons in a tokamak

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The possibility of high post-disruption runaway electron current raises safety-related concerns for large tokamaks, such as ITER. The runaway electrons can quickly replace a large part of the initial current carried by the bulk plasma electrons. The corresponding magnetic energy is typically greater than the particle kinetic energy. This feature separates the time-scale of runaway production from the current decay time-scale. We consider three aspects of the runaway evolution: (1) survival and acceleration of initially hot electrons during thermal quench, (2) multiplication of the runaways via knock-on collisions with the bulk electrons, (3) slow decay of the runaway current under marginal criticality scenario.

Although the avalanche mechanism of RE production [1] is anticipated to be the dominant mechanism in ITER [2], the avalanche multiplication of the runaways after the thermal quench still requires a seed RE current. Our kinetic model of seed formation during impurity-dominated thermal quenches is motivated by pellet injection experiments [3]. We assume instantaneous deposition of impurities within a given flux surface and consider two separate populations of electrons ("hot" and "cold"). The hot population with an initial density n_0 represents the pre-quench current-carrying electrons. The cold population comes predominantly from ionization of the injected impurities. We neglect collisions between the hot electrons and consider only their collisions with the cold background, which implies heavy injection of impurities. The cold electrons are characterized by their Spitzer conductivity with a temperature determined by the power balance condition. The inductive electric field E is calculated under assumption of time-independent current density. We thereby take into account that the magnetic energy does not change significantly during the thermal quench, because the system of interest is highly inductive. A 2D Fokker-Planck equation for the hot electrons and a power balance equation for the bulk plasma are solved self-consistently, with impurity radiation as the dominant energy loss mechanism. The behavior of the hot electron population in the limit of abundant impurities is shown in Fig.1. The nearly isotropic initial distribution (green contours) transforms into a beam-like distribution (red contours). The electric field rises until the hot electrons reach an order-of-unity anisotropy and enter the runaway regime.

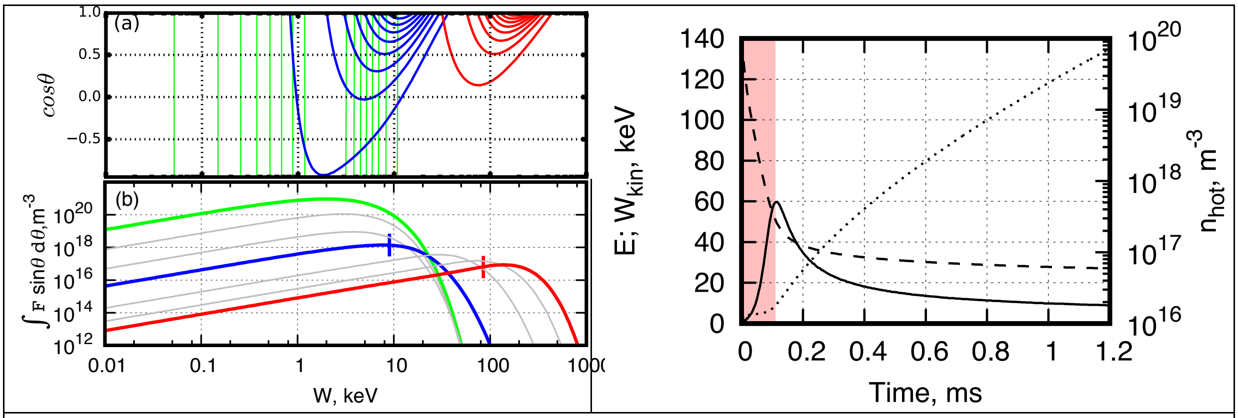

Fig. 1. Left: snapshots of the hot electron distribution (a) and its isotropic part (b) during thermal quench at 0 ms (green), 0.1 ms (blue) and 1.4 ms (red). The contours in (a) mark 0.9, 0.8 ... 0.2 of the maximum. The vertical strokes mark the entrance energies to the runaway regime. Right: inductive electric field (solid), hot electron density (dashed), and mean kinetic energy (dotted).

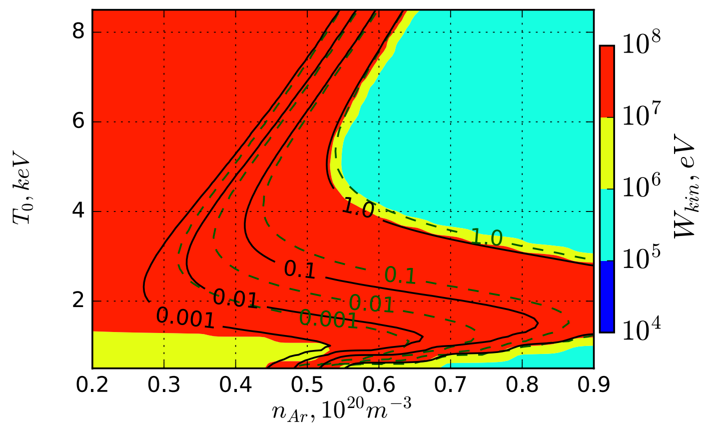

Fig. 2. Contour plots (solid lines) of the surviving hot population normalized to the initial density, for a range of initial electron temperatures and injected impurity densities. The current density is 1MA/m^2. The dashed contours represent an analytical estimate for comparison. Color-coded is the mean kinetic energy of the hot population.

Our model determines the post-thermal-quench (but pre-current-quench) runaway electron density, energy and current for a broad range of initial plasma parameters (density, current density, temperature and impurity concentration), including those of interest for ITER. We find that runaway formation is less efficient in plasmas with high pre-quench temperatures. In particular, we do not expect any significant runaway seed in a 10 keV plasma with a density of 10^{20}m^{-3} when the amount of injected argon is less than $6{\bullet}10^{19}$m^{-3}, while in a 2 keV plasma of the same density a significant runaway population forms if $3{\bullet}10^{19}$m^{-3} of argon is injected. We also find that runaway production increases for heavier injection of impurities up to prompt conversion of the total pre-quench current into the runaway current in the case of abundant impurities. The mean kinetic energy of the runaway population is in this case limited to moderate values (sub-MeV), asymptotically approaching to those of the near-threshold regime [4]. The developed model also predicts that non-uniformity of the plasma

allows the post-quench current to be carried by two distinct runaway populations (a sub-MeV and an ultra-relativistic), which appears to be consistent with the DIII-D observations [5].
The trend for the inductive electric field to decrease with the growth of the runaway population calls for special attention to the runaway avalanche threshold. There are strong experimental indications [6, 7] that the threshold electric field is greater than the critical Connor-Hastie field [8] needed to overcome the collisional friction for ultra-relativistic electrons, and prior theoretical work [9] attributes this enhancement to synchrotron losses. Yet, the simple dynamical model used in Ref. [9] is too crude for quantitative predictions. To enable such predictions, we have developed a systematic kinetic treatment of the problem, which refines the findings of Ref. [9]. The avalanche time-scale is relatively slow compared to the small-angle collisional processes, especially at the later stage of runaway formation or during the runaway current mitigation. This suggests a two-step approach to the problem. We first ignore the large-angle collisions and study the behavior of pre-existing runaways to find that the runaways tend to form a non-monotonic energy distribution that peaks at a phase space attractor. We then use the resulting distribution of the runaways to predict their multiplication or loss. Our analysis reveals a mechanism for the hysteresis in the evolution of runaways and explains the effect of runaways on the current decay process. We find that there are two different threshold electric fields in this problem: a minimal field required for sustainment of the existing runaway population and a higher field required for the avalanche onset. The new value of the electric field for runaway avalanche onset is higher and the avalanche growth rate is lower than previous predictions (see Fig. 3).

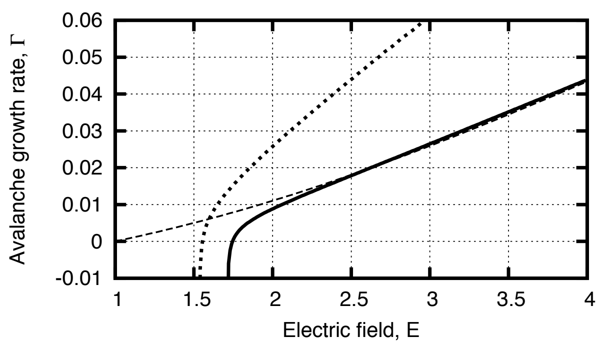

Fig. 3. Dependence of the avalanche growth rate on the normalized inductive electric field (solid curve) in comparison with Ref. [2] (dashed curve) and the growth rate inferred from the model of Ref. [9] (dotted curve).

These findings open a possibility for improved interpretation of the corresponding experiments, including interpretation of the x-ray and synchrotron emission measurements. They also enable substantial improvement of disruption models for ITER [10]. The runaway electron physics is essential for credible modeling plasma dynamics during Vertical Displacement Events (VDE). The existence of threshold electric fields for sustainment and growth of the runaway population determines the decay rate of toroidal current in the runaway mitigation experiments where the avalanche-produced runaway current has to be in a self-sustained regime of marginal criticality if the VDE timescale is much longer than the avalanche timescale. The marginal criticality scenario implies that the inductive electric field is close to the avalanche threshold at every location where the runaway current density is finite, and the current density vanishes at any point where the field is subcritical [11]. This nonlinear 'Ohm's law' governs the profile of the evolving runaway current. A simple analytic example of the current decay under marginal criticality scenario is shown in Figs. 4 and 5.

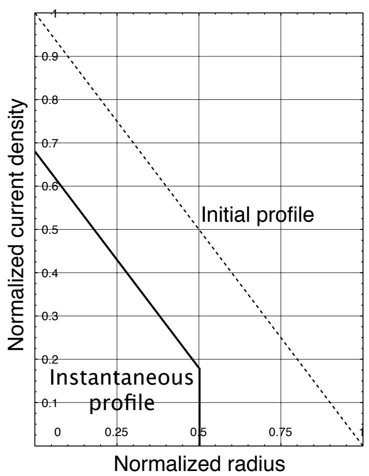

Fig. 4. Snapshot of the current profile during the decay of the runaway current. Note a sharp edge of the current-carrying channel.

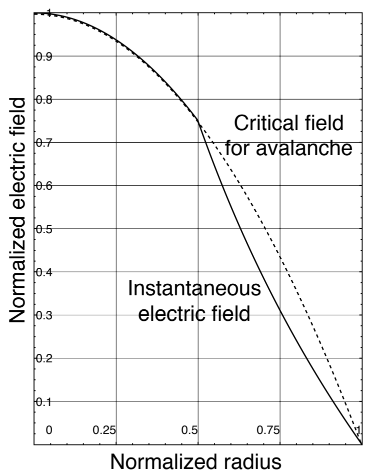

Fig. 5. Radial profile of the electric field for Fig. 4. Note that the electric field is below the critical field outside the current – carrying channel.

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