RUNAWAY ELECTRONS (WHITEPAPER)

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Onset and growth of relativistic avalanche

The compelling need to mitigate runaway electrons or to control their behavior in ITER calls for particular attention to three aspects of the runaway problem: relativistic energies of the runaways, avalanche mechanism of the runaway production, and the combined effect of pitch-angle scattering and synchrotron losses on the runaway distribution function. It is especially important to have an accurate description of the near-threshold regime that represents long-term behavior of the runaways and is critical for the mitigation process. Even very strong initial inductive electric field is reasonably expected to drop down to the threshold-level values with the growth of the runaway population. The key questions in that regard are what is the threshold electric field and what is the growth rate of the avalanche when the electric field exceeds the threshold. There are strong experimental indications [1, 2] that the threshold electric field is greater than the critical field needed to overcome the collisional friction for ultra-relativistic electrons, and prior theoretical work [3, 4] attributes this enhancement to synchrotron losses. These studies need to be extended to self-consistent modeling of the runaway population and the evolving inductive electric field. This next-step model should involve an unabridged description of Moller scattering, which is essential for proper modeling of the near-threshold regime.

Critical role of bulk electron cooling

The runaway avalanche during plasma disruption is commonly assumed to be triggered by thermal quench. Insufficient present understanding of the thermal quench mechanism is a major obstacle for complete predictive modeling of the runaway behavior. Rapid cooling of bulk electrons during thermal quench could result from fast penetration of impurities into the plasma core or from large electron heat flux to the wall along the stochastic magnetic field lines. This ambiguity needs to be resolved because it translates into large uncertainty in the bulk plasma conductivity, which makes it difficult to predict evolution of the inductive electric field. A possible simplified approach is to consider an extreme case in which the bulk plasma is so cold and resistive that the entire current is carried by the runaway electrons. However, the bulk electron current can actually be significant and needs to be calculated systematically rather than simply ignored. The underlying reason is that the inductive electric field causes ohmic heating of the bulk electrons, and the electrons can remain cold only in the presence of some powerful cooling mechanism not just prior to the runaway build-up but also during the build-up. The challenge is to develop a consistent theoretical model for such anomalous cooling of the bulk electrons.

Kinetic instabilities of the runaway beam

Given that pitch-angle scattering and synchrotron losses can limit the runaway energy gain, it is natural to consider micro-instabilities as an opportunity to accelerate energy losses of the runaways via enhanced scattering. In the early tokamaks, such as TM-3, T-6, TFR and others, the "fan" instability [5, 6] was observed frequently in the presence of runaway electrons and interpreted qualitatively on the basis of local stability theory. Yet, the local theory is not completely adequate, because it does not cover the effect of plasma nonuniformity on the excited waves. This includes any system size constraints on the wave growth. Also, the analysis of magnetized plasma waves needed to be extended to other potentially unstable modes. A recently developed ray-tracing code COIN (COnvective INstability) [7] is designed to address these issues and examine kinetic instabilities of a runaway beam for any given equilibrium configuration of the plasma and any distribution function of the RE. This should enable runaway stability assessment for present day machines as well as for ITER. Observations and modeling of runaway-driven micro-instabilities are very likely to have interesting diagnostic applications. This aspect is reminiscent of the highly informative MHD spectroscopy that deals with kinetic instabilities driven by energetic ions.

Interpretation and modeling of critical field experiments

Although the theory suggests that synchrotron losses and pitch-angle scattering tend to prevent the runaway avalanche, it is still a challenge to achieve quantitative agreement between the theory and the experimental reports that the critical electric field for runaway avalanche is several times greater than the threshold value E_c determined by the electron collisional drag. This effort is important because of its potential impact on the runaway mitigation technique. It is likely to require close interaction between theorists and experimentalists in order to take into account additional factors that are not covered by the current idealized models.

Distribution of low-energy electrons

Most theoretical discussions of runaway avalanche imply a beam-like distribution of the current-carrying electrons. The beam-like distribution has actually been observed in experiments [8], but there are also other measurements (TEXTOR, DIIID, JET) that show large population of lower energy electrons with a roughly isotropic angular distribution. The origin of this population and its contribution to the total current still need better understanding. It is plausible that large-angle collisions of the beam-like runaways with bulk plasma electrons create an accompanying population of lower energy particles. An accurate near-threshold modeling of the runaway avalanche in realistic geometry will enable quantification of this mechanism to see whether it can explain the low-energy component of the electron distribution and its potential role in larger machines.

Current drive effect on runaways

The rf-current drive may help to prevent the runaway build-up because the thermal quench and the resulting drop in Spitzer conductivity would not necessarily create a very strong inductive electric field in the presence of rf-current drive. The population of current-carrying electrons tends to be super-thermal in the presence of rf-drive, and the collisional slowing down force for these electrons is therefore relatively insensitive to the bulk electron temperature. This motivates an effort to model the build-up of runaways in the presence of rf-current drive to assess potential benefits of the current drive technique for runaway control and the possibilities to test this approach in present-day experiments.

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