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トカマクディスラプションにおける逃走電子発生の物理モデリングの進展
Progress in Disruption Modeling with Runaway Electrons for Tokamak Plasmas

松山　顕之
MATSUYAMA Akinobu

量研機構
QST

Introduction - In the last decades, much effort has been paid to the development of mitigation schemes of disruption loads in ITER, which is aimed at minimizing heat and electromagnetic loads due to the plasma thermal and magnetic energies within acceptable levels. However, an important challenge still remains – the mitigation of runaway electrons. While the current quench in metallic wall environments such as JET-ILW [1] is observed to be slow enough to avoid runaway generation, the massive impurity injection to mitigate thermal loads shortens the current quench time, which results in runaway generation [2]. A theoretical prediction [3] suggests that mitigated disruptions in ITER are susceptible to runaway generation due to the avalanche growth. In [4], the estimation that a small seed current on the order of 10^{-9}MA can be amplified up to 1 MA runaway current has been reported. A difficulty arises in a large gap of the avalanche growth gain between present tokamaks and ITER [3], which prevents us from straightforward extrapolation of the experimental data towards disruptions with 10 MA-order plasma currents. Therefore – in addition to experimental demonstration of runaway mitigation – to develop predictive models is a mandatory as research in support of ITER.

In this paper, we report our recent progress in modeling of runaway electrons. The runaway generation is governed by complex interaction between various physical processes involved in the mechanisms of thermal and current quenches. This paper focuses on two mechanisms that we recently studied: (1) the effects of MHD activity on runaway generation and (2) mitigation mechanisms by impurities. As the future prospects of our integrated modeling, we also report a development of kinetic modeling on the basis of Monte-Carlo code.

Effects of MHD activity on runaway generation - Runaway electron generation is understood as the conversion of magnetic energy from Ohmic to runaway currents, where the resistive dissipation in a plasma and within the wall dominates its conversion rate [4]. Since post-disruption plasmas are characterized by the low electron temperature around 10 eV, it is natural to consider the resistive instability [5] as a mechanism giving constraints on the runaway current profile. To study such effects of MHD activity, we have developed a resistive MHD code EXTREM [6] that self-consistently couples runaway generation and resistive MHD modes. Figure 1 compares the evolution of runaway current profile calculated by EXTREM with 1D transport calculation, where a profile flattening due to nonlinear resistive kink is simulated. We found that during the evolution of a resistive kink, the inductive electric field associated with the magnetic flux expulsion plays a role of additional channel to enhance the primary current [6]. Figure 2 compares the primary (left) and plateau (right) currents for different electron temperatures; the effect of inductive electric field is seen to be significant at the low temperature and high resistivity condition. Such condition is relevant to mitigated disruptions and our simulation suggests that the resistive instability plays an important role in the generation and redistribution of primary runaway currents.

Mitigation by high Z impurity - Another important topic is a mitigation mechanism of runaway generation by high-Z impurities. Especially, in ITER, massive impurity gases or solid pellets are injected to dissipate thermal energy of bulk plasmas with impurity radiation. We here apply the runaway avalanche model including the contribution of impurity collisions and synchrotron radiation [5] and evaluate the runaway current plateau for Argon and Neon injection. Taking into account the balance between the Ohmic heating and radiation loss $\eta j^2 = n_e n_Z L(T_e)$, one can evaluate the runaway generation rate from the induced electric field $E = \eta j$. The evaluated runaway current plateau is plotted versus the impurity density in Fig. 3 for ITER-like parameters with a given seed current of 10^{-7}MA. A non-monotonic dependence on the impurity density is observed here: At lower impurity density side ($n_Z < 10^{20}\mathrm{m}^{-3}$), the runaway current is seen to increase with the impurity density because the induced electric field increases with the resistivity. Conversely, by further increasing the impurity density up to $10^{21}m^{-3}$, the parameter regime that implies the mitigation by impurity injection appears. This region is characterized by the dissipation of electron energy due the synergetic effects of elastic scattering by impurity atoms and the synchrotron radiation [7]. The recent mitigation experiments direct at the validation of this mechanism and at quantifying the damping rate of runaway current against the impurity content for different gas species.

Advanced Kinetic Modeling by Monte-Carlo methods and Future Directions - Recent progress in the theory of runaway electrons has relied on numerical study using Fokker-Planck codes. Although these codes are accurate enough to analyze the momentum space dynamics of electrons, it is still cumbersome to extend such types of the codes to analyze the spatial dynamics. In the field of energetic particle physics, orbit following Monte Carlo codes are widely used for such purpose. Motivated by this fact, to explore the possibility of orbit-following approach, we develop a new variance reduction technique with the aid of weight window [8] to simulate the runaway distribution function by Monte-Carlo methods. Figure 4 illustrates that transient behavior of the distribution function during Dreicer acceleration is reproduced by our scheme. The new scheme helps us to perform numerical simulations of the runaway dynamics even with weak electric fields near the critical threshold [9]. We start to implement this new scheme to the guiding-center orbit-following code ETC-Rel [10] and plans to address the runaway electron generation in stochastic magnetic fields. The possibility of runaway mitigation by magnetic perturbations is suggested earlier in the pioneering work by Yoshino, et al. [11] but remains to be an open physics issue.

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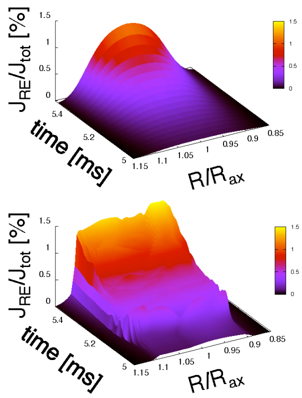

Figure 1: Primary current profiles calculated without (top) and with (bottom) resistive kink modes.

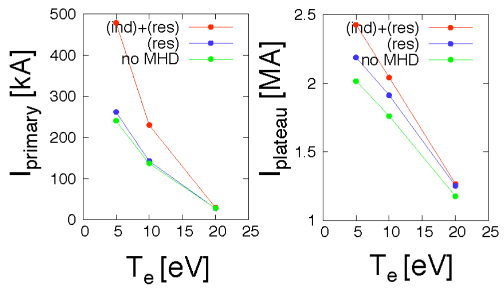

Figure 2: Electron temperature dependence of primary (left) and plateau (right) runaway currents, including resistive (res) and inductive electric fields (ind) driven by m = 1 resistive kink modes.

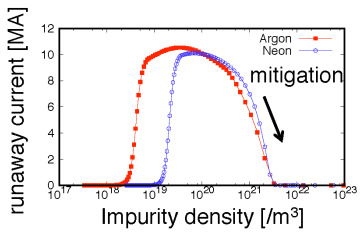

Figure 3: Runaway current plateau with I_{seed} = 10^{-7}MA for ITER parameters (R=6.2m, a=2m, I_p=17MA, B_t=5.3T).

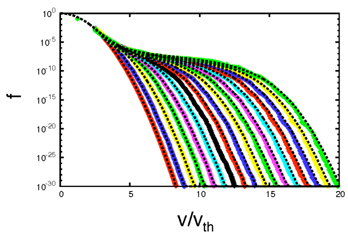

Figure 4: Nonthermal electron distribution function during Dreicer acceleration calculated by Fokker-Planck (dashed) and Monte-Carlo codes (colored points).