Fokker-Planck Simulation of Runaway Electron Generation in Tokamak Disruptions

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The runaway electron (RE) generation during tokamak disruptions is investigated by kinetic simulations. Specifically, three dimensional (two-dimensional in momentum space; one-dimensional in the radial direction) Fokker-Planck simulations are coupled with the self-consistent electric field caused by the disruptions. The thermal quench time is varied, and the results are compared with those of the steady-state solution of the RE generation rate. The hot-tail effect is enhanced when the thermal quench time is shorter than the electron slowing down time.

Keywords: runaway electron, tokamak disruption, Fokker-Planck simulation, induced toroidal field

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Non-thermal effects are required in simulations of runaway electron (RE) generation during tokamak disruptions, for the following reason. If the thermal quench time is sufficiently short, the plasma cools before the high-velocity electrons (whose collision time exceeds the quench time) have thermalized. This rapid cooling forms the high velocity tail of the electron velocity distribution, which enhances the primary RE generation rate and is known as the hot-tail effect.

The hot-tail effect has been discussed by Smith [1] and Fehér [2]. They considered the self-consistent evolution of both the RE generation induced by the hot-tail and the induced electric field. However, in their model the primary REs are divided into two components: hot-tail REs and Dreicer REs. They evaluated the tail formed by thermal quenching by a one-dimensional Fokker-Planck equation, neglecting the electric field and hot-tail REs. The latter constitute the electrons with velocities greater than $v_c = v_{th}(E_D/E)^{1/2}$, where v_{th} is the thermal velocity, and E_D and E are the Dreicer and parallel electric fields, respectively. The Dreicer component has also been described by conventional steady state model [3]. Since these components are intrinsically indivisible, separating them might become problemic if the hot-tail effect is significant. Therefore, to accurately evaluate the RE current, we require a self-consistent description of the momentum distribution and the induced electric field. To our knowledge, such a description is currently lacking.

In this study, we develop a Fokker-Planck code from first principles. The code, named TASK/FP, evolves the relativistic momentum distribution function and the induced field in a self-consistent manner. The momentum distribution function is sufficiently resolved by decomposing the momentum direction domain. The Fokker-Planck equation to be solved is given by

$$\frac{\partial f}{\partial t} = -\nabla \cdot \boldsymbol{S}_{\mathrm{C,E}} \tag{1}$$

$$\boldsymbol{S}_{\mathrm{C,E}} = -\overleftrightarrow{\boldsymbol{D}}_{\mathrm{C}} \cdot \nabla f + \boldsymbol{F}_{\mathrm{C,E}} f, \tag{2}$$

where ∇ is the derivative operator in momentum space. In this study, $\overleftrightarrow{\boldsymbol{D}}_{\mathrm{C}}$ and $\boldsymbol{F}_{\mathrm{C}}$ are determined from the weak relativistic isotropic background collision term [4] with a relativistic Maxwellian. The electric field resulting from the diffusion and RE generation is described by the following equations:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_0 \frac{\partial}{\partial t} j \tag{3}$$

$$j = \sigma_{\mathrm{sp}} E + ecn_{\mathrm{r}} \tag{4}$$

$$\frac{\mathrm{d}n_{\mathrm{rp}}}{\mathrm{d}t} = \int \nabla \cdot \boldsymbol{S}_{\mathrm{C,E}} \mathrm{d}\boldsymbol{p} \tag{5}$$

$$\frac{\mathrm{d}n_{\mathrm{rs}}}{\mathrm{d}t} = S_{\mathrm{avalanche}}(n_{\mathrm{r}}, E/E_{\mathrm{C}}), \tag{6}$$

where σ_{sp} is the Spitzer conductivity, and n_{rp} and n_{rs} are the primary and secondary RE densities, respectively. The total RE density n_{r} is given by $n_{\mathrm{r}} = n_{\mathrm{rp}} + n_{\mathrm{rs}}$. The primary RE density (calculated using Eq. (5)) evolves by electrons dispersing in the momentum calculation domain: $0 < p < p_{\max}$ and $p_{\max}^2/m \sim 1\,\mathrm{MeV}$. The secondary RE generation rate (Eq. (6)) is a function of n_{r} and E/E_{C} [5] (where $E_{\mathrm{C}} = E_{\mathrm{D}}(v_{\mathrm{th}}/c)^2$) rather than f, because the secondary RE generation rate is insensitive to the primary RE energy [6]. In Eq. (3), which express the diffusion of E, closure is provided by Ohm's law (Eq. (4)). All REs are assumed to travel at the velocity of light with no collisions.

In the following calculation, the temperature of the

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Table 1 JT-60U like plasma parameters.

Radii & Elongation	$R = 3.4\,\mathrm{m}$, $a = \sqrt{\kappa} \times 1.0\,\mathrm{m}$ $\kappa = 1.6$
Initial plasma current current dens. prof.	$I_\mathrm{P} = 1.052\,\mathrm{MA}$ $j(\rho) = j_0(1 - \rho^{1.74})^{3.23}$
Initial & final temp.	$T(0,0) = 2\,\mathrm{keV}$, $T_\mathrm{f}(0) = 10\,\mathrm{eV}$
Electron dens.	$n_\mathrm{e}(0) = 4 \times 10^{19}\mathrm{m}^{-3}$, $Z_\mathrm{eff} = 3$

background plasmas obeys:

$$T(t,\rho) = (T(0,\rho) - T_\mathrm{f}(\rho))\exp(-t/\tau_\mathrm{q}) + T_\mathrm{f}(\rho)$$
$$T_\mathrm{f}(\rho) = T_\mathrm{f}(0)(1 - 0.9\rho^2), \tag{7}$$

where ρ is the normalized minor radius, τ_q is a parameter of the thermal quench time, and T_f is the post-quench plasma temperature. Electrons and ions are assumed to exist at the same temperature. The parameters of the JT-60U like plasma are tabulated in Table 1.

The RE generation during thermal quenching is evaluated in the presence (case A) and absence (case B) of the hot-tail effect. In case A, f and E are evolved, and the primary RE generation rate is calculated by Eqs. (1)-(5). In case B, the primary RE generation rate is calculated by Conner's expression [3] $\mathrm{d}n_\mathrm{rp}/\mathrm{d}t = S_\mathrm{conner}(E/E_\mathrm{D}, T)$ rather than by Eq. (5). As this expression neglects the hot-tail effect, simulations of case A and B should yield different results.

Figure 1 shows the time evolution of the primary RE, total RE, and net currents during tokamak disruption in cases A and B. In these simulations, $\tau_\mathrm{q} = 0.15\,\mathrm{ms}$. In both cases, the RE current rapidly increases at $t = 0.75\,\mathrm{ms}$ and gradually increases thereafter. The initial rapid increase is dominated by primary RE generation. The following slow increase is mainly caused by secondary RE generation. The primary RE generation is apparently enhanced by the hot-tail effect. The momentum distributions in the parallel direction at different times (with $\tau_\mathrm{q} = 0.15\,\mathrm{ms}$) are plotted in Fig. 2. The initial slopes (extrapolated by the auxiliary black dotted lines) are thermalized to the quenching temperature. The remainders of the curves constitute the non-thermalized tail. Figure 3 correlates the RE current ratio to the initial current and the thermal quench time. The hot-tail effect becomes remarkable at thermal quench times below 0.25 ms. The threshold value can be approximately interpreted as the electron-electron slowing down time $\tau_\mathrm{s}^\mathrm{ee}$. When the electron velocity $v \gg v_\mathrm{th}$, the slowing down time is given by the following:

$$\tau_\mathrm{s}^\mathrm{ee}(v) = 0.5\frac{4\pi\epsilon_0^2 m_\mathrm{e}^2 v^3}{n_\mathrm{e} q^4 \ln\Lambda}. \tag{8}$$

Here, pre-quench thermal velocity v_th0 is much greater than the post-quench thermal velocity v_thf; that is, $v_\mathrm{th0} \gg v_\mathrm{thf}$. If the thermal quench time exceeds the slowing down time of almost all of electrons, the momentum distribution forms no tail, and the hot-tail effect is suppressed. Since most of the electrons travel at less than a few times v_th0, the slowing down time of their velocities is a suitable threshold

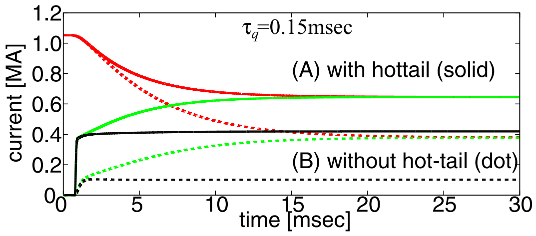

Fig. 1 Evolutions of the simulated plasma current in case A (hot-tail effect; solid lines) and B (no hot-tail effect; dotted lines) with $\tau_\mathrm{q} = 0.15\,\mathrm{ms}$. Red, green, and black lines plot the net current, RE current, and primary RE current, respectively.

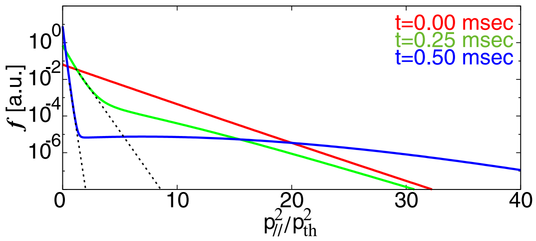

Fig. 2 Momentum distribution in the $p_\parallel$ ($p_\perp \sim 0$) direction at several time steps ($\tau_\mathrm{q} = 0.15\,\mathrm{ms}$). The momentum is normalized by the initial thermal momentum.

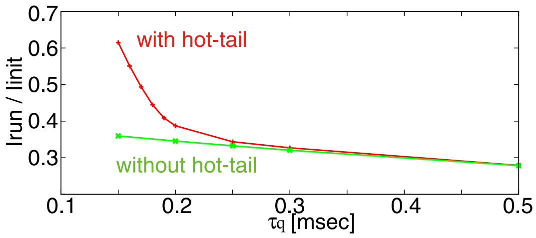

Fig. 3 RE current (relative to the initial current) versus thermal quench time.

criterion. In our simulation, the e-e slowing down time (and hence the approximate threshold) is determined as $\tau_\mathrm{s}^\mathrm{ee}(3v_\mathrm{th0}) \sim 0.26\,\mathrm{ms}$.

The mitigation method of disruptions such as Massive Gas Injection (MGI) is attributed to the short thermal quench time, which would enhance the hot-tail effect in ITER. It should be investigated as a future work.

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