21st NEXT Workshop

Fokker-Planck simulation for runaway electron generation including the hot-tail effect

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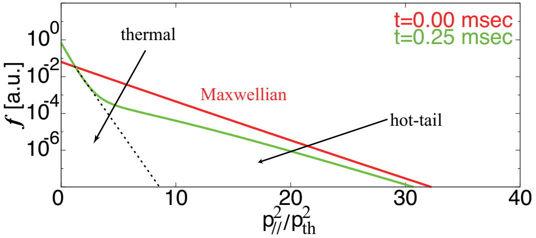
Introduction (RE generation in disruptions)

- Runaway Electrons (REs) are generated in tokamak disruptions.
- The impact of REs to the first wall leads intolerable heat load especially in ITER.
- The high electron density plasma achieved by MGI may suppress the RE generation because of high collisionality.
- MGI shortens the thermal quench and might enhance the RE generation through the hot-tail effect.
    - This requires the kinetic treatment.
- The estimation of the amount of REs generated in tokamak disruption is required for the development of the mitigation method.

Introduction (hot-tail effect)

- Non-thermal effect should be included for RE gen. simulation
  - If the drop of T is sufficiently fast, the plasma cools down so quickly that fast electrons do not have enough time to be thermalized.
  - The rapid cooling forms the high velocity tail of f_e.
  - It enhances the primary RE generation and this effect is called as hot-tail effect.



- For mitigated disruptions, the thermal quench time tends to be shortened.

Equations

Electric field diffusion

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

Ohm's law

$$j = \sigma_{sp} E + ecn_r, \quad n_r = n_{rp} + n_{rs}$$

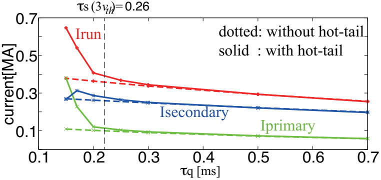
Primary and seconadary RE generation rate

$$\frac{dn_{rp}}{dt} = -\int \frac{\partial f}{\partial t} d\boldsymbol{p}, \quad (p_{max}^2/m \sim 0.5\mathrm{MeV}), \quad \frac{dn_{rs}}{dt} = S_{avalanche}(n_r, E/E_C)$$

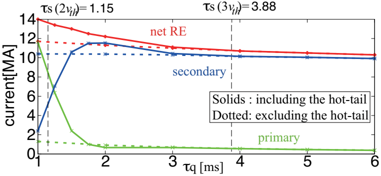
Temperature

$$T(t) = (T(0) - T(t_{\max}))\exp(-t/\tau_q) + T(t_{\max}), \quad T(t_{\max}) = 10\mathrm{eV}$$

Threshold of the hot-tail effect



JT-60U like (Ip=1MA)



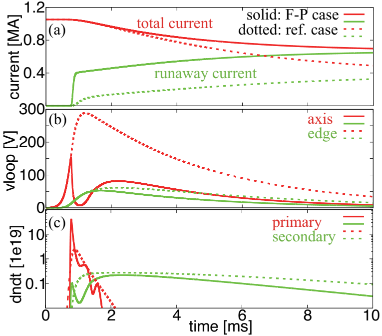
ITER like (Ip=15MA)

- If the thermal quench time τ_q is shorter than $\tau_s^{ee}(2 - 3v_{th})$, the hot-tail effect becomes remarkable.

$$\tau_s^{ee}(v) = \frac{2\pi\epsilon_0^2 m_e^2 v^3}{n_e q^4 \ln\Lambda}$$

- The hot-tail effect enhances the primary RE current.
- The high primary RE current reduces the secondary RE current.

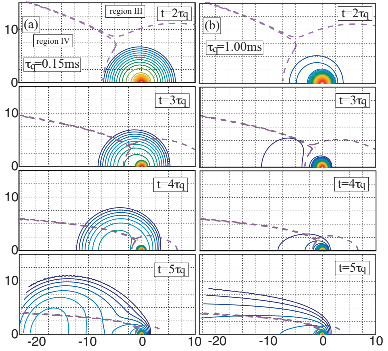
Evolutions (JT-60U case)



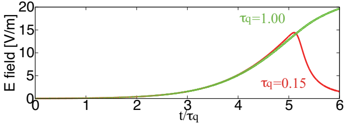
- Evolutions of current, loop voltage, and RE gen. rate on magnetic axis
- $\tau_q = 0.15$ ms ($\tau_s^{ee}(3v_{th}) = 0.26$ ms)
- dotted: excluding the hot-tail
- solid: including the hot-tail

- The hot-tail effect enhances the RE current. (fig. a)
- the peak value of the primary RE gen. rate is an order magnitude greater. (fig. (c))
- The E field including the hot-tail sharply drops (fig. (b))
  - owing to the high primary RE gen. rate.
- Once the E field decreases, it re-increases gradually. (fig. (b))
  - The hollow E profile is filled by E diffusion.

Hot-tail affects the RE distribution (JT-60U case)



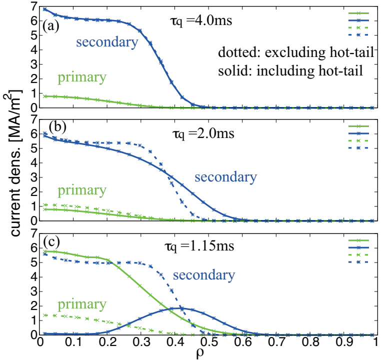
- left: $\tau_q = 0.15$ ms (hot-tail effective)
- right: $\tau_q = 1.0$ ms (ineffective)
- dashed curve: RE-nonRE boundary derived by Fussmann[NF **19**, 327, (1979)]



- E field is similar until $t = 5\tau_q$ in both cases.

- The hot-tail effect makes f_e broad to the $p_\perp$ direction.
- There are a lot of hot-tail electrons, which have finite perpendicular momentum (See $t = 2 - 3\tau_q$)
- Collisional pitch angle scattering also affects the broadening.

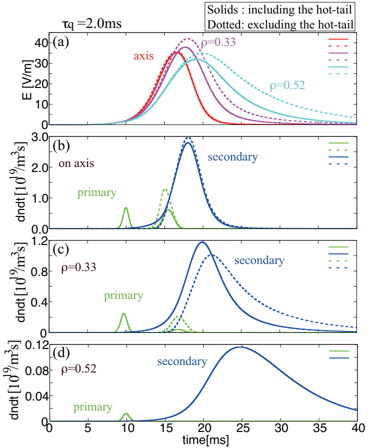
RE current density profile (ITER like)



- $\tau_s^{ee}(3v_{th}) = 3.88$ms

- RE j profiles are in good agreement for $\tau_q < \tau_s(3v_{th})$.
- For $\tau_q = 2.0$ ms, the secondary RE j profile including the hot-tail effect becomes broader.
  - The hot-tail effect reduces the primary RE j around $\rho = 0$ and enhances it in outer region ($\rho > 0.4$) in invisible magnitude.
- For $\tau_q = 1.15$ ms, the hot-tail effect dominates the primary RE j on-axis.
- The secondary RE j has a hollowed profile.

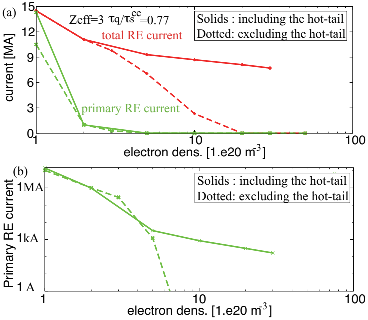
Evolutions of E and dn/dt for $\tau_q = 2.0$ms (ITER)



- (a): E field at several radial point.
- (b)-(d): RE gen. rate.

- The hot-tail effect divides the peak of the primary RE gen. into two. ($t \sim 10$ and $t \sim 15$ms)
  - Former is the hot-tail generation.
- The hot-tail electrons can be REs even with the weak E ($E/E_C \sim 20$ at $t = 10$ms).
- REs generated at the earlier time trigger the secondary gen.
- Earlier onset on the secondary gen. maintains E weaker.
- Subsequent primary gen. decreases
  - The primary gen. is sensitive to E.

Density dependence



- (a) Primary and secondary RE current against electron density.
- (b) Focused on the primary RE
- $\tau_q/\tau_s = 0.77$ (fixed)
- Evolution of n_e is omitted.

- The high density $n_e \sim 10^{21}\mathrm{m}^{-3}$ may suppress RE current (excluding hot-tail).
- If $\tau_q/\tau_s < 1$ is kept
  - Hot-tail maintains $0.1 - 1$kA even if $n_e > 10^{21}\mathrm{m}^{-3}$
  - Primary REs are multiplied to $\sim$MA.
- Reliable τ_q in mitigated plasma is required.

Summary

- RE generation including hot-tail effect has been investigated.
- The hot-tail effect affects to the RE current, the evolution of E, j profile, RE velocity distribution, and density dependence even in secondary dominant case.
- There are potentials that
  - RE velocity distribution affects to synchrotron rad.
  - If the mitigation shortens the thermal quench sufficiently, hot-tail effect makes innegligible RE current.