Fokker-Planck Simulation of the Runaway Electron Generation in Tokamak Disruption

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Introduction (RE generation)

- The importance of the Runaway Electron (RE) generation study during tokamak disruption:
  - Thermal quench due to tokamak disruption induces strong totoidal electric field.
  - Because of the low collisionality for high velocity, some of electrons are accelerated to relativistic high energy.
  - The impact to the first wall leads crucial localized heat load.
  - To avoid this, several mitigation methods are developed.
- The estimation of the amount of REs during tokamak disruption is required for the development of the operation scenarios.

Introduction (hot-tail effect)

- Non-thermal effect should be include for RE gen. simulation
  - If the thermal quench is enough short, the plasma cools down so quickly that high velocity electrons do not have enough time to thermalize.
  - The rapid cooling forms the high velocity tail of the electron velocity distribution.
  - This tail enhances the primary RE generation and this effect is called as hot-tail effect.
  - Since the mitigation, such as Massive Gas Injection (MGI), makes the thermal quench time to be short, the estimation of the hot-tail effect is important for ITER.
- In order to include the hot-tail effect to RE generation simulation, we have developed a Fokker-Planck code TASK/FP.

Simulation Code: TASK/FP

- TASK/FP is a Fokker-Planck code to calculate the time evolution of momentum distribution function f in 3 dimension : (p, θ, ρ).

Fokker-Planck equation in $(p,\ \theta,\ \rho)$ coordinate

$$\frac{\partial f_s}{\partial t} = -\nabla_{p,\rho} \cdot \boldsymbol{S} = -\frac{1}{p^2}\frac{\partial}{\partial p}p^2 S_p - \frac{1}{p\sin\theta}\frac{\partial}{\partial\theta}\sin\theta S_\theta - \frac{1}{\rho}\frac{\partial}{\partial\rho}\rho S_\rho$$

Elements of flux

$$S_p = -D_{pp}\frac{\partial f}{\partial p} - D_{p\theta}\frac{1}{p}\frac{\partial f}{\partial\theta} + F_\rho f$$

$$S_\theta = -D_{\theta p}\frac{\partial f}{\partial p} - D_{\theta\theta}\frac{1}{p}\frac{\partial f}{\partial\theta} + F_\theta f, \qquad S_\rho = -D_\rho\frac{\partial f}{\partial\rho} + F_\rho f$$

Equations 1: E field

- The induced electric field obeys:

1. Diffusion equation of E field

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

- Ohm's low is adopted as a closure.

2. Ohm's low (n_r: REs density, σ_{sp}: Spitzer conductivity)

$$j = \sigma_{sp} E + ecn_r$$

- This equation assumes
  - The velocity of all REs equals to that of light.
  - All of REs are collisionless.

Equations 2: RE gen. rate

- There are two kind of RE generation mechanisms, primary and secondary.
  - The primary RE generation is defined as the electrons go out from the computational domain as:

3. Primary RE generation rate

$$\frac{dn_{rp}}{dt} = \int \nabla \cdot \boldsymbol{S} d\boldsymbol{p}, \quad (p_{max}^2/m \sim 1\text{MeV})$$

  - Secondary RE generation rate is expressed as a function of RE density n_r and E/E_C:

4. Secondary RE generation rate

$$\frac{dn_{rs}}{dt} = S_{avalanche}(n_r, E/E_C)$$

  - $E_C = E_D(v_{th}/c)^2$

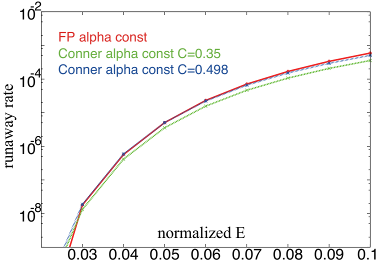
Benchmark: primary RE gen. rate

- In order to confirm the influence of the hot-tail effect, we implement the other primary RE generation rate derived by Conner and Hastie (1975) which do not consider the hot-tail effect.

3-2. Primary RE generation rate without hot-tail effet

$$\frac{dn_{rp}}{dt} = S_{dreicer}(E/E_D, T)$$

- Under the condition of the steady electric field and constant background temperature, the values of these primary RE gen. rate have good agreement.



Parameters (JT-60U like)

- Initial profiles (impurity species: C)

$$
\begin{aligned}
R &= 3.4\text{m},\ \kappa = 1.6,\ a = \sqrt{\kappa} \times 1\text{m} \\
n_e(\rho) &= (0.4 - 0.04)(1 - \rho^2)^{2/3} + 0.04 \quad [\times 10^{20}] \\
T(\rho) &= (2.0 - 0.2)(1 - \rho^2)^2 + 0.2 \quad [keV] \\
j(\rho) &= j_0(1 - \rho^{1.74})^{3.23} \\
n_D(\rho) &= (0.24 - 0.024)(1 - \rho^2)^{2/3} + 0.024 \quad [\times 10^{20}] \\
Z_{eff} &= 3,\ I_{init} = 1.052\text{MA}
\end{aligned}
$$

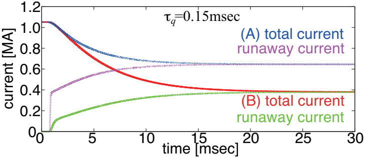
- Thermal quench model

$$
\begin{aligned}
T(t,\rho) &= (T(0,\rho) - T_f(\rho)) * \exp\left(-t/\tau_q\right) + T_f(\rho) \\
T_f(\rho) &= T_f(0)(1 - 0.9\rho^2)
\end{aligned}
$$

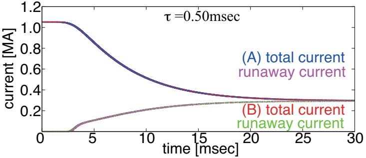
- τ_q: thermal quench time, $T_f(0) = 10\text{eV}$: post-quench temperature

1) Evolutions of current

- Time evolution of the net plasma current and RE current
  - (A): with hot-tail, (B): without hot-tail



$\tau_q = 0.15$msec

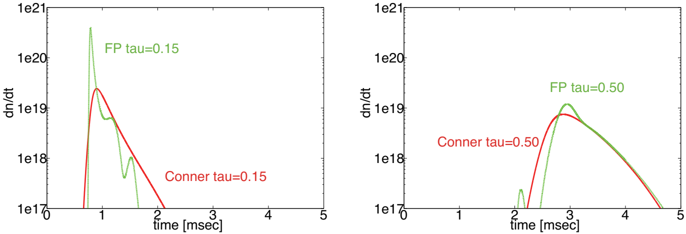


$\tau_q = 0.50$msec

- The RE current increase due to the hot-tail effect.
- The differences between A and B becomes larger as the thermal quench time becomes shorter.

2) Evolutions of dn/dt

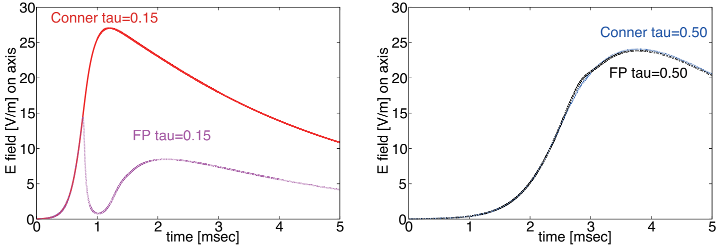
- Time evolution of dn_{rp}/dt
- Focus on $0 < t < 5$msec: primary REs are generated mainly



- For faster thermal quench case ($\tau_q = 0.15$msec), the hot-tail effect enhances the peak value of dn_{rp}/dt and the duration of RE gen. decreases.
- For slower thermal quench case, the hot-tail effect is not remarkable.

3) Evolutions of E

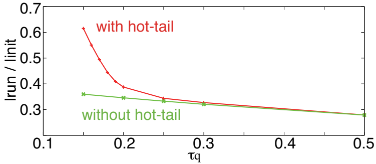
- Time evolutions of $E_{\|}$ on axis
  - (L): $\tau_q = 0.15$msec, (R): $\tau_q = 0.50$msec

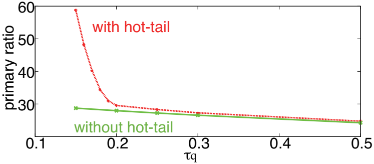


- The strong peak of dn_{rp}/dt reduces $E_{\|}$ for $\tau_q = 0.15$msec
- For the slow quench case, the hot-tail effect is also not remarkable to $E_{\|}$.

4) hot-tail formation

- (L): relation between I_{run}/I_{init} and τ_q
- (R): primary RE current ratio (I_{prim}/I_{run}) v.s. τ_q

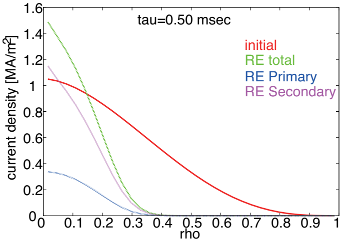


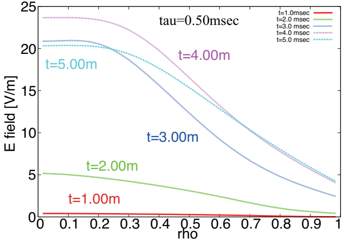


- The hot-tail effect is notable for $\tau_q < 0.25$msec
  - If the thermal quench time is longer than the e-e slowing down time of almost all electrons, it is presumed that the tail of f is not formed.
  - $\tau_{ee}^s(v) = 2\pi\epsilon_0^2 m^2 v^3 / n_e q^4 \ln\Lambda$
  - $\tau_{ee}^s(3v_{th0}) \sim 0.26$msec in this case.
  - Since the most of electrons have the velocity $0 < v < 3v_{th0}$, the hot-tail effect is not effective for $\tau_q > 0.25$msec.

4) radial profiles-1

- (L): current density prifile ($\tau_q = 0.50$msec)
- (R): electric field profile ($\tau_q = 0.50$msec)

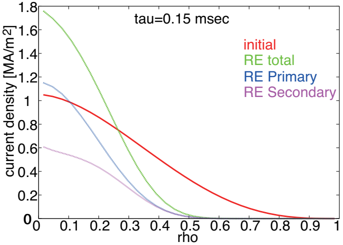


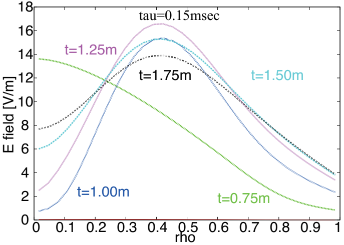


- RE current density profile is peaked on axis.
  - $n_{rp}/n_r = 0.247$ (FP)
  - $n_{rp}/n_r = 0.242$ (Conner)
- E has flat profiles during disruption on axis.

5) radial profiles-2

- (L): current density prifile ($\tau_q = 0.15$msec)
- (R): electric field profile ($\tau_q = 0.15$msec)

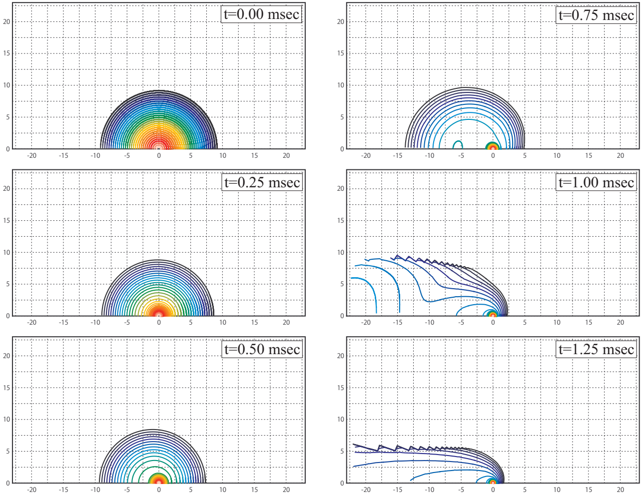




- Faster thermal quench enhances the primary ratio
  - $n_{rp}/n_r = 0.588$ (FP)
  - $n_{rp}/n_r = 0.287$ (Conner)
- Due to the high primary RE gen. rate on axis, E has hollow profiles.

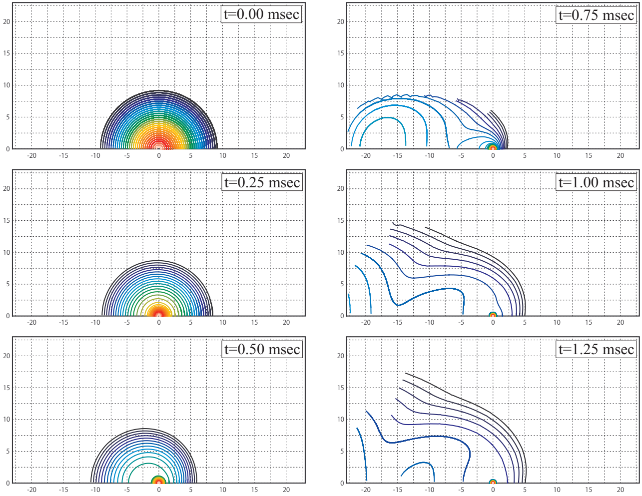
6) f in 2D momentum space-1

- The evolution of the momentum distribution function ($\tau_q = 0.20$)



7) f in 2D momentum space-2

- The evolution of the momentum distribution function ($\tau_q = 0.15$)



Summary

- RE generation including hot-tail effect were simulated.
    - If the temperature drops quickly enough, the hot-tail effect becomes remarkable.
    - In the relatively-slow thermal quench cases, $\tau_q > 0.25$msec, Fokker-Planck primary RE gen. rate returns similar results to that of analytical one.
    - It seems that thermal quench time affects the pitch angle of REs.
    - The threshold value of τ_q which affects hot-tail effect can be estimated from the slowing down time τ_s