*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-1.030 (2008)*

Hot tail runaway electron generation in tokamak disruptions

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Hot tail runaway electron generation in tokamak disruptions is caused by incomplete thermalization of the electron velocity distribution during the rapid plasma cooling. Electrons at high velocities in the initial Maxwellian, where the electron collision time is longer than the cooling time, are in a transient phase left as a hot tail of the distribution. The part of this tail above the runaway threshold energy can easily be converted to runaways by the rising electric field.

Analytical estimates of the hot tail runaway generation have previously been found for a type of cooling history, in which the cooling rate $d\ln T/dt$ is proportional to the collision frequency of thermal electrons [1, 2]. In reality however, one can expect the cooling rate to decrease with time rather than to be proportional to the rising collision frequency. This is because the cooling rate can be lower at temperatures closer to the ionization energies and because processes like Ohmic heating and collisions with ions become important at the low temperatures in the end of the thermal quench. In this work, we therefore study the exponential-like cooling history

$$T = T_{\text{final}} + (T_0 - T_{\text{final}})e^{-t/t_0}. \tag{1}$$

The cooling is assumed to be caused by strongly radiating impurities, and the supra-thermal electrons are mainly slowed down by collisions with thermal electrons. This is modelled by the kinetic equation and the collision operator

$$\frac{\partial f}{\partial t} = \mathcal{C}(f) + S, \tag{2}$$

$$\mathcal{C}(f) = \frac{\nu_0 v_{T0}^3}{v^2}\frac{\partial}{\partial v}2G\left(\frac{v}{v_T}\right)\left(\frac{v^2}{v_T^2}f + \frac{v}{2}\frac{\partial f}{\partial v}\right), \tag{3}$$

where v_T is the thermal velocity, ν is the collision frequency, subscript 0 denotes an initial value, and G is the Chandrasekhar function. The radiative loss term S is concentrated at low energies and is assumed to cool the plasma according to Eq. (1). We want to find an approximate solution to Eq. (2). An analytical solution for $v \gg v_T$ for instantaneous cooling is given by $f \propto e^{-(v^3/v_{T0}^3+\nu_0 t)^{2/3}}$, so we propose an ansatz for the distribution f of the form

$$f = \frac{n_0}{\pi^{3/2}v_{T0}^3}\exp\left[-\left(\frac{v^3}{v_{T0}^3}+3\tau\right)^{2/3}\right] + A\frac{n_0}{\pi^{3/2}v_T^3}\exp\left[-\frac{v^2}{v_T^2}\right]. \tag{4}$$

Velocity moments $\int dv\, v^k$ of Eq. (2) are used to determine the parameters $\tau(t)$ and $A(t)$, which have the initial values $\tau = 0$, $A = 0$. The first moment $k = 2$ (particle conservation) implies

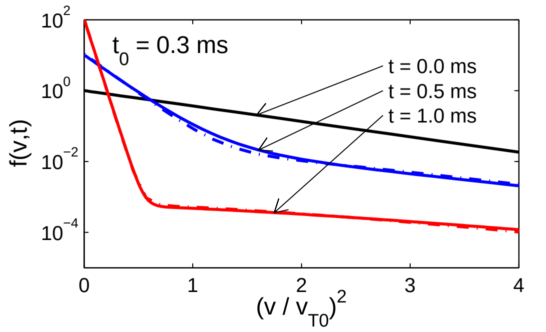

Figure 1: The electron distribution function for the case $T_0 = 3.1$ keV, $T_{\text{final}} = 0.01T_0$, $n_0 = 2.8 \cdot 10^{19}$ m^{-3} and $t_0 = 0.3$ ms. The result of the moment analysis Eq. (6) (dash-dotted) is compared with a numerical simulation of Eq. (2) (solid).

that $A = \text{erf}[(3\tau)^{1/3}] - (2/\sqrt{\pi})(3\tau)^{1/3}e^{-(3\tau)^{2/3}}$. Our aim is to model the evolution of the tail, so a high value of $k = 15-20$ is used in the second moment

$$\frac{d}{dt}\int_0^\infty v^k f dv = \int_0^\infty v^k \mathcal{C}(f)dv. \tag{5}$$

By inserting the ansatz (4) this can be written as a first order differential equation for τ,

$$\frac{d\tau}{dt} = \frac{\frac{\pi^{3/2}}{n_0}\int_0^\infty v^k\mathcal{C}(f)dv - A\frac{\Gamma\left(\frac{k+1}{2}\right)}{2}\frac{dv_T^{k-2}}{dt}}{2\Gamma\left(\frac{k+1}{2}\right)v_T^{k-2}e^{-w^2}/\sqrt{\pi} - 2I_k/v_{T0}^3}, \tag{6}$$

where

$$I_k = \int_0^\infty v^k\left(\frac{v^3}{v_{T0}^3} + 3\tau\right)^{-1/3} e^{-\left(\frac{v^3}{v_{T0}^3}+3\tau\right)^{2/3}} dv. \tag{7}$$

Figure 1 shows that the ansatz function with $\tau(t)$ taken from Eq. (6) is very close to a full numerical solution of Eq. (2). The hot tail runaway rate is obtained by integration over the runaway region of velocity space [2].

$$\frac{dn_{\text{run}}^{\text{h}}}{dt} \simeq -\frac{du_{\text{c}}}{dt}\frac{2u_{\text{c}}^2 H(-du_{\text{c}}/dt)}{(u_{\text{c}}^3 - 3\tau)^{1/3}}\int_{u_{\text{c}}}^\infty \frac{e^{-u^2}u^2du}{(u^3-3\tau)^{2/3}}, \tag{8}$$

where H is the Heaviside function and $u^3 = v^3/v_{T0}^3 + 3\tau$. An empirical approximation to the result of Eq. (6) is $\tau \simeq \nu_0(t-t_0)$ for $t/t_0 \gtrsim 3$. This approximation can be used to obtain a crude estimate of the number of hot tail runaways $n_{\text{run}}^{\text{h}} \simeq n_0(2/\sqrt{\pi})u_{\text{c,min}}e^{-u_{\text{c,min}}^2}$, where

$$u_{\text{c,min}}^3 = \frac{4}{3}t_0\nu_0\left[1 + \frac{3}{2}\ln\frac{E_{\text{D0}}}{2E_0} - \ln\left(\frac{4}{3}t_0\nu_0\right)\right] - 3t_0\nu_0. \tag{9}$$

The hot tail runaway generation in Eq. (8) has been added to the known runaway rates for Dreicer and avalanche runaway generation, which together with the induction equation

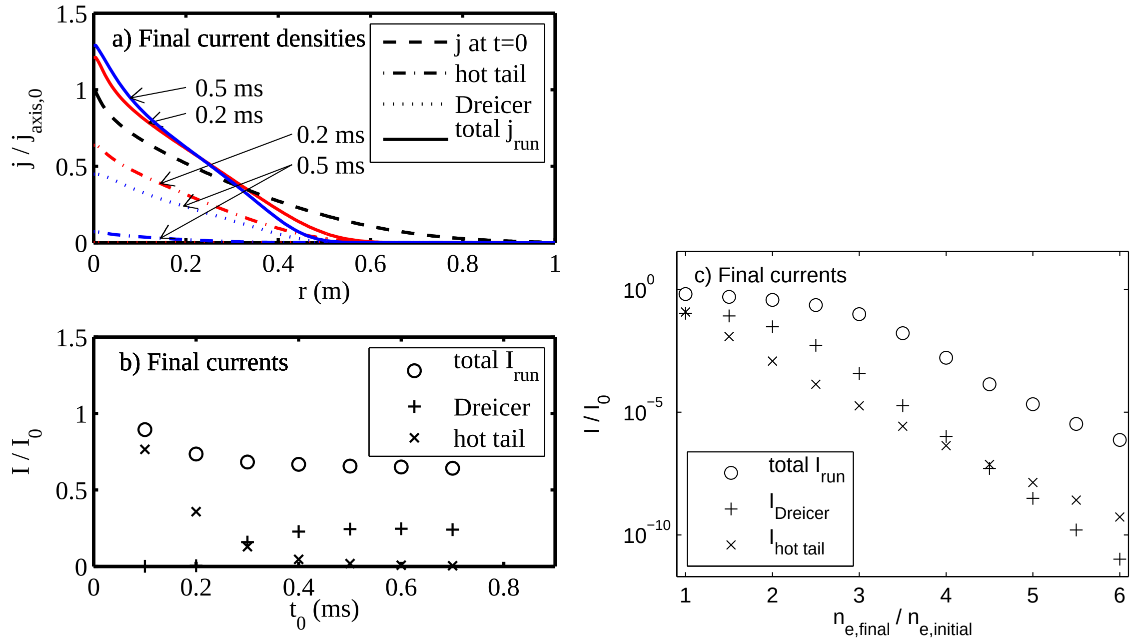

Figure 2: Left: JET disruption simulations for $B = 3$ T, $R = 3$ m, $a = 1$ m, $I_0 = 1.9$ MA, $n = (1 - 0.9(r/a)^2)^{2/3} \cdot 2.8 \cdot 10^{19}$ m^{-3}, $T_0 = (1 - 0.9(r/a)^2)^2 \cdot 3.1$ keV, $T_{\text{final}} = (1 - 0.9(r/a)^2) \cdot 10$ eV, and different thermal quench times. a) Current density profiles produced by hot tail and Dreicer runaway generation and final runaway current density for $t_0 = 0.2$ ms and 0.5 ms. b) Final currents and runaway currents due to hot tail and Dreicer generation. Right: JET disruption simulations for $T_{\text{final}} = 15$ eV on axis and $t_0 = 0.3$ ms where n_e increases on the cooling time scale to different final electron densities $n_{e,\text{final}}$.

$\nabla^2 E = \mu_0 \frac{\partial}{\partial r} (\sigma E + j_{\text{run}})$, are used to simulate runaway generation in a disruption [3, 4]. An example of such a simulation for JET in Figs. 2a-b shows that the hot tail runaway mechanism dominates over the Dreicer mechanism for short thermal quench times ($t_0 \lesssim 0.3$ ms). Other simulations show that in contrast to Dreicer generation, the hot tail runaway production is rather insensitive to the post-disruption temperature T_{final} for low T_{final}. With a few modifications, the above theory can also be used for time varying densities. One finds, see Fig 2c, that the Dreicer production generally becomes more suppressed than the hot tail production by an increased electron density. Simulations for ITER show that hot tail generation will dominate over Dreicer generation if the thermal quench time is of the same order as in JET. Figure 3 shows that when hot tail generation is included in the simulation, it makes the current profile less peaked on-axis than a model including only Dreicer and avalanche generation would predict. This can be important for the post-disruption plasma stability.

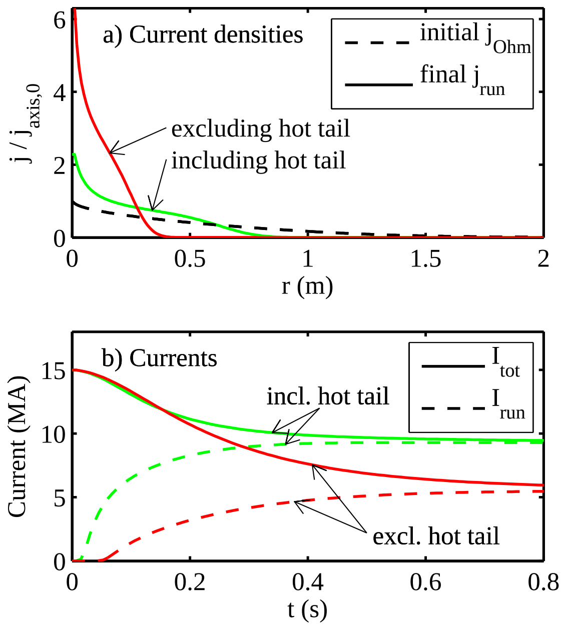

Figure 3: ITER simulation with and without hot tail runaway generation using the disruption parameters $T_0 = 30$ eV, $t_0 = 1$ ms and $n_{\text{final}}/n_0 = 2$.

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