Runaway electron generation during plasma shutdown by pellet injection

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To mitigate the harmful effects of tokamak disruptions, such as large mechanical and thermal loads on the vessel and damage caused by runaway electrons, it has been proposed that "killer" pellets could be injected in order to safely terminate the discharge. The aim of this technique is to cool the plasma to a temperature low enough to give a fast current quench, but not so low that runaway electrons are generated. In the present work, we use a pellet ablation code [1] to determine the initial plasma cooling and the amount of deposited material at each flux surface. This information is passed on to a runaway code [2], which has been further developed to model the evolution of the temperature, the densities of different ion charge states, the electric field, and the runaway electron density [3].

The ablated material from the pellet forms an expanding cloud. In the direction perpendicular to the magnetic field the expansion stops when ionisation sets in at the cloud periphery, which leads to the formation of a series of clouds along the pellet path. The expansion along the field lines is described by a 1D Lagrangian pellet code, which also models the penetration of ambient plasma particles, the atomic processes (radiation and ionisation) in the cloud, and the pellet ablation. The code self-consistently models the heat flow Q into the cloud and the concomitant reduction of the background electron temperature $T_{\rm e}^{\rm bg}$, through the equation

$$\frac{d}{dt}\left[\frac{3}{2}n_{\rm e}^{\rm bg}T_{\rm e}^{\rm bg}V_{\rm bg}\right] = -Q,$$

where $n_{\rm e}^{\rm bg}$ is the electron density, and $V_{\rm bg}$ is the volume between two nearby flux surfaces enclosing the cloud.

The runaway code models all quantities as functions of the minor radius, so the output from the pellet code is flux surface averaged before it is passed on to the runaway code. When averaging the electron density, both the background electrons and the colder cloud electrons can be considered to be thermal compared to the runaways, so their densities are just added, $n_{\rm e} = n_{\rm e}^{\rm bg} + n_{\rm e}^{\rm cloud}V_{\rm cloud}/V_{\rm bg}$. The average temperature is given by $n_{\rm e}T_{\rm e} = n_{\rm e}^{\rm bg}T_{\rm e}^{\rm bg} + n_{\rm e}^{\rm cloud}T_{\rm e}^{\rm cloud}V_{\rm cloud}/V_{\rm bg}$, and the different ion charge state populations are assumed to become uniformly distributed on the flux surfaces.

The temperature drop causes the induction of a high toroidal electric field, which can generate runaways through the Dreicer and avalanche processes at the rate

$$\frac{dn_{\rm run}}{dt} \simeq \frac{n_{\rm e}}{\tau}\left(\frac{m_{\rm e}c^2}{2T_{\rm e}}\right)^{3/2}\left(\frac{E_{\rm D}}{E}\right)^{3(1+Z_{\rm eff})/16} e^{-\frac{E_{\rm D}}{4E}-\sqrt{\frac{(1+Z_{\rm eff})E_{\rm D}}{E}}} + n_{\rm run}\sqrt{\frac{\pi}{2}}\frac{E/E_{\rm c}-1}{3\tau\ln\Lambda},$$

where $\tau = 4\pi\varepsilon_0^2 m_{\rm e}^2 c^3/(n_{\rm e}e^4\ln\Lambda)$, $E_{\rm c} = m_{\rm e}c/(e\tau)$, $E_{\rm D} = m_{\rm e}^2c^3/(e\tau T_{\rm e})$. The evolution of the electric field is governed by the parallel component of the induction equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_0\frac{\partial}{\partial t}\left(\sigma_\parallel E + n_{\rm run}ec\right),$$

where $\sigma_\parallel = \sigma_\parallel(T_{\rm e}, Z_{\rm eff}, \varepsilon)$ is the parallel Spitzer conductivity with a neoclassical correction at the high initial temperatures, and the runaways are assumed to travel at the speed of light. This equation governs how the Ohmic current decays due to replacement by the runaway current and electric field diffusion out of the plasma. The electric field also varies due to changes in the conductivity $\sigma_\parallel$, so the temperature evolution has to be modelled in the runaway code. This is done by solving the three energy balance equations for electrons, deuterons and pellet ions,

$$\frac{3}{2}\frac{\partial(n_{\rm e}T_{\rm e})}{\partial t} = \frac{3n_{\rm e}}{2r}\frac{\partial}{\partial r}\chi r\frac{\partial T_{\rm e}}{\partial r} + P_{\rm OH} - P_{\rm line} - P_{\rm Br} - P_{\rm ion} + P_{\rm c}^{\rm eD} + P_{\rm c}^{\rm ep},$$

$$\frac{3}{2}\frac{\partial(n_{\rm D}T_{\rm D})}{\partial t} = \frac{3n_{\rm D}}{2r}\frac{\partial}{\partial r}\chi r\frac{\partial T}{\partial r} + P_{\rm c}^{\rm De} + P_{\rm c}^{\rm Dp},$$

$$\frac{3}{2}\frac{\partial(n_{\rm p}T_{\rm p})}{\partial t} = \frac{3n_{\rm p}}{2r}\frac{\partial}{\partial r}\chi r\frac{\partial T}{\partial r} + P_{\rm c}^{\rm pe} + P_{\rm c}^{\rm pD}.$$

The energy exchange in collisions is $P_{\rm c}^{kl} = 3n_k(T_l - T_k)/(2\tau_{kl})$, with the heat exchange time

$$\tau_{kl} = \frac{3\sqrt{2}\pi^{3/2}\varepsilon_0^2 m_k m_l}{n_l e^4 Z_k^2 Z_l^2\ln\Lambda}\left(\frac{T_k}{m_k} + \frac{T_l}{m_l}\right)^{3/2}.$$

The electrons gain energy from Ohmic heating $P_{\rm OH} = \sigma_\parallel E^2$, and lose energy by ionization $P_{\rm ion}$, Bremsstrahlung $P_{\rm Br}$ and line radiation $P_{\rm line}$. The line radiation is the sum of the radiation for each charge state $P_{{\rm line},i} = n_i n_{\rm e} L_i(n_{\rm e}, T_{\rm e})$. The evolution of the individual charge state densities n_i are determined by the impact ionisation and the radiative recombination rates.

The pellet code simulations show that the initial rapid plasma cooling during the residence time of the pellet is determined mainly by the speed of the pellet, i.e. the time it spends in each location. The penetration depth on the other hand is determined mainly by the pellet size. When the temperature is flux surface averaged, it is found that the cooling caused by deuterium pellets is principally due to dilution of the background plasma by the cloud particles, whereas impurity pellets cause mostly radiative cooling.

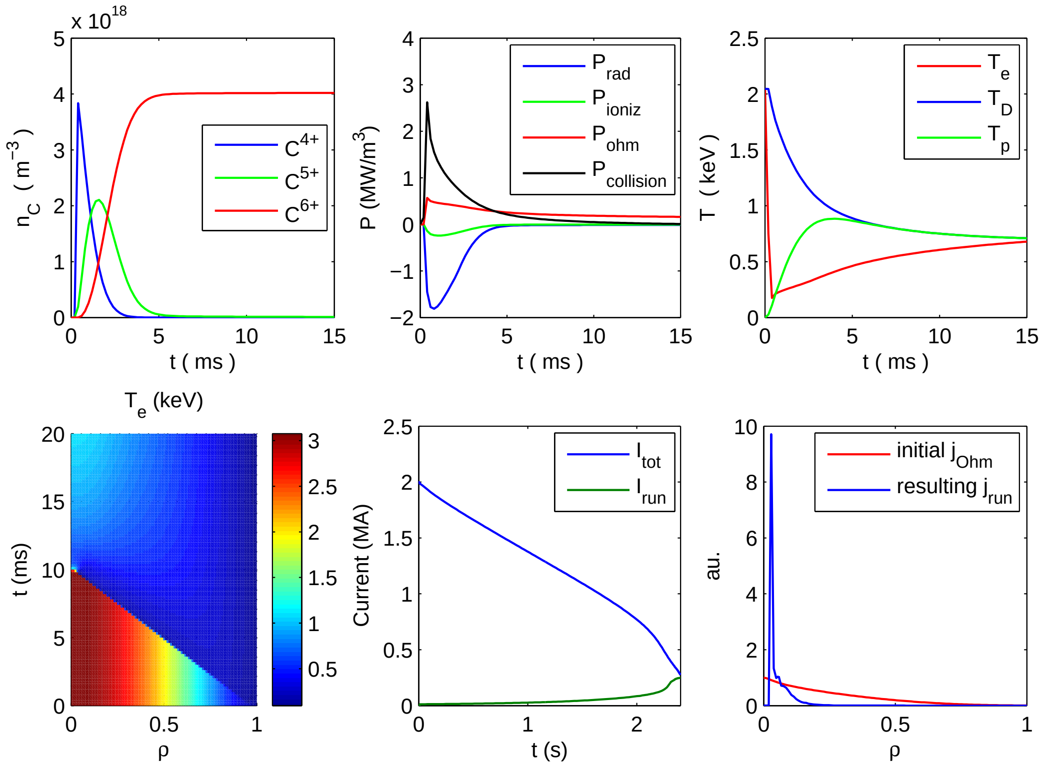

Figure 1: Simulation of a $v_p = 100$ m/s, $r_p = 0.9$ mm carbon pellet, with $\chi = 1$ m^2/s. Top plots show $\rho = r/a = 0.5$: Left: Carbon ionisation. Middle: Electron energy loss and gain. Right: Temperatures of electrons, deuterons and pellet ions. Bottom: Left: Electron temperature. Middle: Ohmic and runaway currents. Right: Current densities.

Simulations were made for injection of deuterium and carbon pellets into JET-like plasmas. Deuterium pellets have the advantage that they drastically increase the plasma density, which prevents runaway formation since $E_c \propto n_e$. On the other hand, since deuterium only dilutes the plasma, a very large (~ 1 cm) pellet or very many pellets must be injected in order to reduce the temperature enough to obtain a fast current quench. Carbon pellet injection produces a much more efficient cooling, but it does not increase the electron density significantly, since the evaporation energy of carbon is two orders of magnitude higher than for deuterium. Carbon pellets are therefore prone to generate runaways.

It was found that fast carbon pellets do not produce runaways, but the cooling is inefficient, so the current quench times become very long. Slow ($\lesssim 100$ m/s) pellets that penetrate to the central part of the plasma cool more but also produce runaways. The local cooling is more efficient the deeper the pellet penetrates, because the flux surfaces are smaller at lower radii. The runaway population is therefore largest at the radius corresponding to the pellet penetration depth. Once most pellet ions are fully ionised, Ohmic heating dominates over the losses and

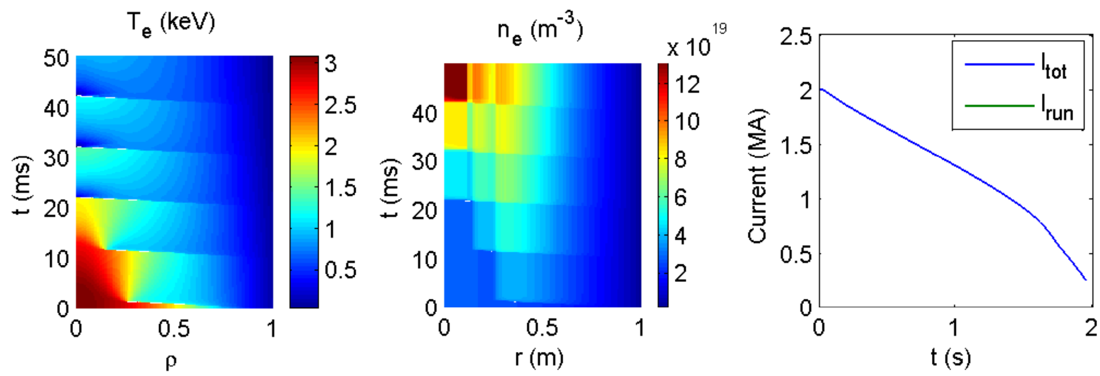

Figure 2: Multiple $v_p = 500$ m/s, $r_p = 0.6$ mm carbon pellets. Left: Electron temperature. Middle: Thermal electron density. Right: Ohmic current.

reheats the plasma, see Fig. 1. This prolongs the current quench to ~ 2 s, which is too long to be able to avoid large vessel forces due to vertical displacement events. The post-thermal quench balance between Ohmic heating and radiation reported for high Z material pellets [4] is not reached in our single carbon pellet simulations. Multiple carbon pellet injection, simulated in Fig. 2, is more promising, although a situation where the heating and radiation powers are of the same order has in simulations so far only been obtained in the central part of the plasma. The advantage with multiple pellets is that the first few pellets do not cool enough to produce runaways, but they increase n_e, which prevents runaway generation when the following pellets enter. It is therefore important that the time delay between pellets is long enough so that the carbon becomes fully ionised, but short enough so that the reheating is still small.

In conclusion, a tool has been developed to test the suitability of different pellet injection scenarios for disruption mitigation. In the future it will be further developed in order to be able to simulate carbon doped deuterium pellets, and make predictions for ITER.

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