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Simulation of runaway electron generation during plasma shutdown by doped pellet injection

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Disruptions can cause serious damage already in present day tokamaks and their effect can be even more dangerous in larger devices. To avoid or ameliorate disruptions it has been proposed that discharges can be terminated by “killer” pellet injection. High Z impurity pellets can cool down the plasma effectively through isotropically distributed radiation but a significant amount of runaway electrons can be produced. Runaway generation can be avoided by massive hydrogen pellet injection, but the cooling is not effective in this case. Impurity-doped hydrogen isotope pellets can combine the advantages of the two methods [1].

The Hybrid pellet code [2] was modified to model impurity doped deuterium pellets. In this model we assume that impurities only change the energy balance of the cloud. If impurities are present in the pellet cloud the heat absorbed by the cloud from the background plasma is mainly radiated, and only a small part of the energy is transformed to the internal energy of the cloud similarly to killer pellets.

The change of the energy balance of the cloud by strongly radiating impurities increases the toroidal size of the cloud compared to pure deuterium clouds. The size of the cloud is important, as it determines the heat absorption from perpendicular direction. As the cloud absorbs energy from the plasma, the electron temperature of the plasma will start to decrease already during the lifetime of the pellet cloud. Adiabatic energy exchange is assumed from between two nearby flux surfaces separated by the cloud diameter $2R_{\rm cld}$, and the energy absorption is calculated as:

$$\frac{d}{dt}\left[\frac{3}{2}n_{\rm e}^{\rm bg}T_{\rm e}^{\rm bg}V_{\rm bg}\right] = -2\pi R_{\rm cld}q_{\|}(R_{\rm cld}+z_{\rm cld}\cdot q_{\perp}/q_{\|}), \qquad (1)$$

where $z_{\rm cld}$ is the length of the deuterium cloud in toroidal direction. $q_{\|}$ and $q_{\perp}$ are the parallel and perpendicular heat fluxes ($q_{\perp}/q_{\|} \sim 5\%$).

After the pellet leaves its cigar shaped cloud (flux tube) to form a new one, the particles from the pellet cloud will spread out over the flux surface. It is assumed that the electron density increases exponentially ($\Delta n \sim (1-e^{-t/t_0})$) with $t_0 = 0.1$ ms homogenization time.

The electrons originating from the cloud are assumed to be heated up instantaneously, as the electron-electron collision time is small. The background plasma temperature changes accordingly. The ions have longer collision times, so they are modeled separately, and coupled to the electrons with collisional energy exchange terms: $P_{\mathrm{c}}^{kl} = 3n_k(T_l - T_k)/(2\tau_{kl})$, where the heat exchange time is $\tau_{kl} = \frac{3\sqrt{2}\pi^{3/2}\varepsilon_0^2 m_k m_l}{n_l e^4 Z_k^2 Z_l^2 \ln\Lambda}\left(\frac{T_k}{m_k}+\frac{T_l}{m_l}\right)^{\frac{3}{2}}$, and subscripts k,l refers to electrons (e), deuterium ions (D) and ions from the pellet (p).

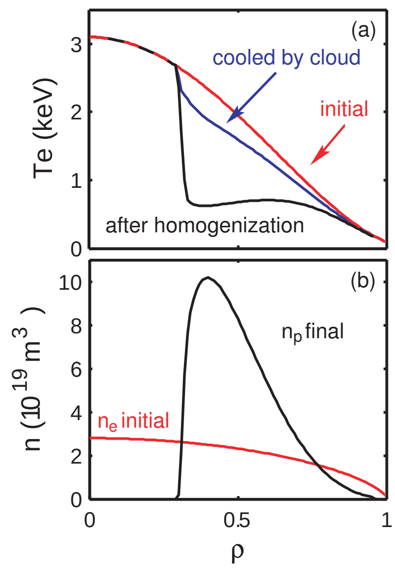

Figure 1: The cooling and material deposition for a 1% carbon doped deuterium pellet with r_{p} = 1.6 mm, v_{p}=1000 m/s

Figure 1 shows the initial cooling caused by the doped pellet in a JET-like plasma. The red line denotes the initial electron temperature, the blue line is the temperature of the background plasma electrons when the pellet leaves its cloud. The pellet cloud has a cooling effect that can be several hundreds of electronvolts. The black curve on Figure 1(a) shows the electron temperature after homogenization. The high ablation rate of the doped pellet will result a huge density increase (Figure 1(b)).

During and after homogenization runaway electron generation and the current quench time is calculated by the runaway code [3]. The temperature will change due to Ohmic heating ($P_{\mathrm{OH}} = \sigma_{\|}E^2$), ionization ($P_{\mathrm{ion}}$), Bremsstrahlung ($P_{\mathrm{Br}}$) and line radiation ($P_{\mathrm{line}} = \sum_i n_i n_{\mathrm{e}} L_i(n_{\mathrm{e}}, T_{\mathrm{e}})$) power losses. Line radiation is the sum of the radiation for each charge state and n_i evolves due to electron impact ionization and the radiative recombination. A simple heat diffusion model is implemented ($\chi = 1\ m^2 s^{-1}$, averaged gyro-Bohm value). The following equations will determine the temperature evolution:

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

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

$$\frac{3}{2}\frac{\partial(n_{\mathrm{p}}T_{\mathrm{p}})}{\partial t} = \frac{3n_{\mathrm{p}}}{2r}\frac{\partial}{\partial r}\left(\chi r\frac{\partial T_{\mathrm{p}}}{\partial r}\right) + P_{\mathrm{c}}^{\mathrm{pe}} + P_{\mathrm{c}}^{\mathrm{pD}}. \tag{4}$$

Figure 2 shows the temperature change at $\rho = 0.5$ according to equations (2-4). The initial high radiation will cool the plasma during and after the homogenization further more, but as the

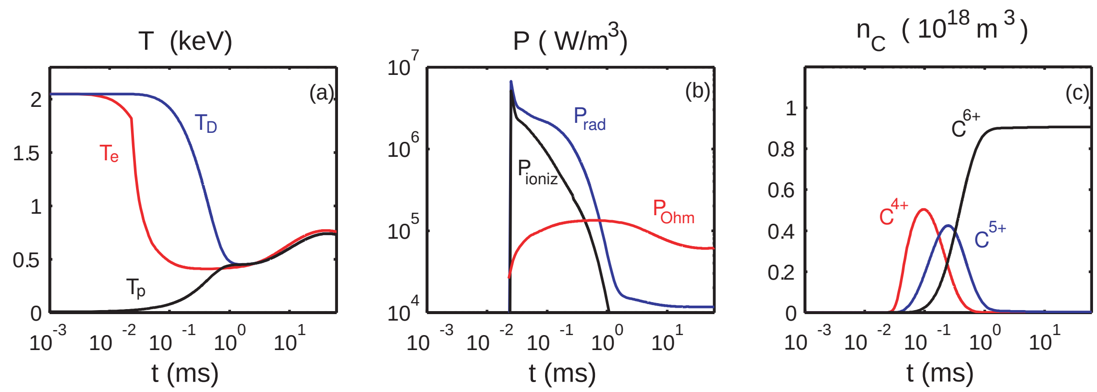

Figure 2: Simulations for a 1% carbon doped deuterium pellet with $v_{\mathrm{p}} = 1000$ m/s and $r_{\mathrm{p}} = 1.6$ mm at $r/a = 0.5$. Time evolution of the (a) temperature of electrons, background ions and pellet ions; (b) of the radiation, ionization and ohmic heating power densities. The pellet enters the flux-tube at t=0. The power densities are shown after the time when the pellet has left the flux-tube at $t = 0.02$ ms. (c) The different ionization stages of carbon.

carbon atoms become fully ionized, the strong Ohmic heating will start to reheat the plasma. Afterwards the cooling will be determined by the slow diffusion process.

As the plasma cools and its conductivity drops ($\sigma_{\|} \sim T_{\mathrm{e}}^{3/2}$), an electric field will be raised that tries to keep the current constant. Maxwell equations and Ohm's law will give the following equation for toroidal component of the electric field:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_0 \frac{\partial}{\partial t}\left(\sigma_{\|}E + n_{\mathrm{run}}ec\right). \tag{5}$$

If the electric field rises above the critical field ($E_{\mathrm{c}} = m_{\mathrm{e}}c/(e\tau)$) runaway electrons can be produced. Two primary runway generation mechanism are considered in this study: Dreicer and hot tail runaway generation. This is an extension of our earlier studies, when only Dreicer runaway production was taken into account at a rate of [3]:

$$\frac{dn^D_{\mathrm{run}}}{dt} \simeq \frac{n_{\mathrm{e}}}{\tau}\left(\frac{m_{\mathrm{e}}c^2}{2T_{\mathrm{e}}}\right)^{3/2}\left(\frac{E_{\mathrm{D}}}{E}\right)^{3(1+Z_{\mathrm{eff}})/16} e^{-\frac{E_{\mathrm{D}}}{4E}-\sqrt{\frac{(1+Z_{\mathrm{eff}})E_{\mathrm{D}}}{E}}} \tag{6}$$

where $\tau = 4\pi\varepsilon_0^2 m_{\mathrm{e}}^2 c^3/(n_{\mathrm{e}}e^4 \ln\Lambda)$ and $E_{\mathrm{D}} = m_{\mathrm{e}}^2 c^3/(e\tau T_{\mathrm{e}})$.

Hot tail runaways are calculated with the analytical estimate [4]:

$$\frac{dn^h_{\mathrm{run}}}{dt} \simeq -\frac{du_c}{dt}\frac{2u_c^2 \mathrm{H}(-du_c/dt)}{v/v_{T0}}\int_{u_c}^{\infty}\frac{e^{-u^2}u^2du}{(v/v_{T0})^2}, \quad u^3 = \frac{v_c^3}{v_{T0}^3} + 3\mathrm{H}(t-t_0)\frac{n_{\mathrm{final}}}{n_0}\nu_0(t-t_0) \tag{7}$$

v_c is the critical velocity corresponding to the critical electric field E_c, $u_c = u(v = v_c)$, H is the Heaviside function, ν_0 is the initial electron-electron collision frequency, n_0 is the initial density and v_{T0} denotes the initial thermal velocity of electrons. The final temperature after homogenization is still several hundred eV, so this method underestimates the produced runaway density. It is planned to improve the model by solving the Fokker-Planck equation numerically.

The number of runaways is further enhanced by the avalanche mechanism at the rate [3]:

$$\frac{dn_{\rm run}^{\rm a}}{dt} \simeq n_{\rm run}\frac{E/E_{\rm c}-1}{\tau\ln\Lambda}\sqrt{\frac{\pi\varphi}{3(Z_{\rm eff}+5)}}\sqrt{\left(1-\frac{E_{\rm c}}{E}+\frac{4\pi(Z_{\rm eff}+1)^2}{3\varphi(Z_{\rm eff}+5)(E^2/E_{\rm c}^2+4/\varphi^2-1)}\right)}, \quad (8)$$

where $\varphi = (1+1.46\varepsilon^{1/2}+1.72\varepsilon)^{-1}$ and $\varepsilon = r/R$ denotes the inverse aspect ratio.

For current quench calculation a scenario is chosen where the carbon doped pellet penetrated close to the plasma center, cooling it down considerably (Figure 3). As the temperature drops the electric field exceeds the initial critical field, but the density increase is enough to suppress runaway generation. However, the current quench time is too long, because the plasma is reheated by Ohmic heating.

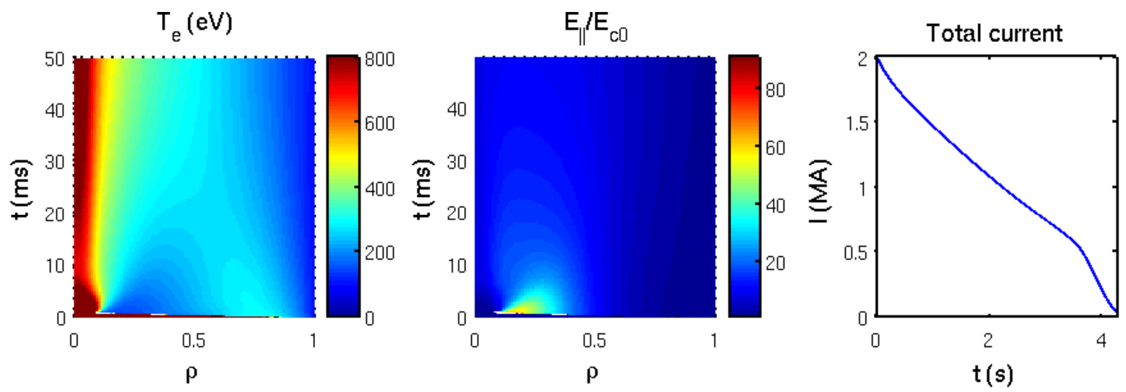

Figure 3: A simulation of a carbon doped deuterium pellet with $r_{\rm p} = 2.3$ mm and $v_{\rm p} = 1000$ m/s and 1% carbon. The evolution of (a) the temperature, (b) the electric field (normalized to the initial E_c) on a short time scale and (c) the resulting current quench.

To mitigate disruptions by doped pellets the current quench should be fast, therefore deuterium pellets needs to be doped by higher Z doping material such as Neon or Argon which is the subject of our ongoing studies. Both Dreicer and hot tail runaways are hoped to be suppressed by these pellets even in large devices such as ITER.

References

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