Simulation of runaway electron generation during plasma shutdown by impurity injection

T. Fehér[1,2], H. M. Smith[1], T. Fülöp[2], K. Gál[3]

[1] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, Greifswald, Germany*

[2] *Dept. of Applied Physics, Chalmers University of Technology and Euratom-VR Association, Göteborg, Sweden*

[3] *MTA KFKI RMKI, Association EURATOM, Budapest, Hungary*

Disruptions are dangerous events in tokamak experiments that can cause serious damage. To prevent this, the plasma can be terminated in a controlled way by injecting impurities before the onset of the disruption [1]. In this work we study such plasma shutdown scenarios for ITER using different concentrations of neon and argon impurities.

Impurities cool down the plasma by isotropic radiation, which reduce the peak heat loads to the wall. The cooling of the plasma is modelled by 1D energy balance equations for electrons, plasma ions and impurities [2]

$$\frac{3}{2}\frac{\partial(n_\mathrm{e}T_\mathrm{e})}{\partial t} = \frac{3n_\mathrm{e}}{2r}\frac{\partial}{\partial r}\left(\chi r\frac{\partial T_\mathrm{e}}{\partial r}\right) + P_\mathrm{OH} - P_\mathrm{line} - P_\mathrm{br} - P_\mathrm{ion} + P_\mathrm{c}^\mathrm{eD} + P_\mathrm{c}^\mathrm{eZ}, \tag{1a}$$

$$\frac{3}{2}\frac{\partial(n_\mathrm{D}T_\mathrm{D})}{\partial t} = \frac{3n_\mathrm{D}}{2r}\frac{\partial}{\partial r}\left(\chi r\frac{\partial T_\mathrm{D}}{\partial r}\right) + P_\mathrm{c}^\mathrm{De} + P_\mathrm{c}^\mathrm{DZ}, \tag{1b}$$

$$\frac{3}{2}\frac{\partial(n_\mathrm{Z}T_\mathrm{Z})}{\partial t} = \frac{3n_\mathrm{Z}}{2r}\frac{\partial}{\partial r}\left(\chi r\frac{\partial T_\mathrm{Z}}{\partial r}\right) + P_\mathrm{c}^\mathrm{Ze} + P_\mathrm{c}^\mathrm{ZD}, \tag{1c}$$

including Ohmic heating ($P_\mathrm{OH} = \sigma_\parallel E^2$), 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 the charge state densities n_i evolve due to electron impact ionization and radiative recombination. The heat diffusion coefficient is assumed to be constant $\chi = 1\ \mathrm{m^2 s^{-1}}$. The different species are coupled with collisional energy exchange terms: $P_\mathrm{c}^{kl} = 3n_k(T_l - T_k)/(2\tau_{kl})$, where $\tau_{kl} = 3\sqrt{2}\pi^{3/2}\varepsilon_0^2 m_k m_l/(n_l e^4 Z_k^2 Z_l^2 \ln\Lambda)\,(T_k/m_k + T_l/m_l)^{3/2}$ is the heat exchange time and subscripts k and l refer to electrons (e), deuterium ions (D) and impurities (Z).

The complicated process of how the impurities enter the plasma is not addressed in this work. It is assumed that the final impurity profile $n_\mathrm{final}(r)$ is proportional to the initial plasma density profile $n_0(r)$. The level of the final impurity density n_final is varied between the different simulations. We assume that the impurity density $n_\mathrm{Z}(r,t)$ increases exponentially to its final value according to $n_\mathrm{Z} = (1 - e^{-t/t_h})n_\mathrm{final}$ on the time scale $t_h = 1$ ms. To achieve a reasonably short current quench time, and thereby reduce the impulse transferred to the vessel, the plasma should be cooled to a low temperature. As the plasma cools and its conductivity drops ($\sigma_\| \sim T_e^{3/2}$), an electric field rises to keep the current constant. The toroidal component of the electric field is described by the following equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_0 \frac{\partial}{\partial t}\left(\sigma_\| E + n_{\rm run} ec\right). \qquad (2)$$

The total current is the sum of the Ohmic and runaway currents, $n_{\rm run}$ is the runaway electron density and it is assumed that the runaways travel with the speed of light.

When the electric field is higher than the critical electric field ($E_{\rm c} = m_{\rm e}c/(e\tau)$), electrons above the critical velocity($v_{\rm c} = v_T\sqrt{E_D/2E}$) can be accelerated to relativistic speeds. Here $E_{\rm D} = m_{\rm e}^2c^3/(e\tau T_{\rm e})$ is the Dreicer field, and τ is the relativistic electron collision time $\tau = 4\pi\varepsilon_0^2 m_{\rm e}^2 c^3/(n_{\rm e}e^4 \ln\Lambda)$. In this work the velocity space dynamics of electrons is not modelled in detail, we only consider the total runaway density $n_{\rm run}$. This density evolves according to the following equation:

$$\frac{\partial n_{\rm run}}{\partial t} = \left(\frac{\partial n_{\rm run}}{\partial t}\right)^{\rm Dreicer} + \left(\frac{\partial n_{\rm run}}{\partial t}\right)^{\rm hot\ tail} + \left(\frac{\partial n_{\rm run}}{\partial t}\right)^{\rm avalanche} + \frac{1}{r}\frac{\partial}{\partial r} r D_{\rm RR}\frac{\partial n_{\rm run}}{\partial r}. \qquad (3)$$

The Dreicer mechanism produces runaways by velocity space diffusion into the runaway region due to small angle collisions [3]

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

The impurities can cause very rapid cooling, in that case the high energy part of the distribution cannot follow the cooling of the bulk plasma. An elevated hot tail of the distribution function can remain, and can become runaway electrons if the critical velocity decreases. The distribution function of energetic electrons is calculated by solving a simplified Fokker-Planck equation taking only the collisions with the Maxwellian bulk of the electron distribution into account [4]

$$\frac{\partial f}{\partial t} = C(f) = \frac{e^4 \ln\Lambda n}{8\pi\varepsilon_0^2 m_e}\frac{1}{v^2}\frac{\partial}{\partial v}\left[v^2 G(v/v_T)\left(\frac{1}{T}f(v) + \frac{1}{m_e v}\frac{\partial f(v)}{\partial v}\right)\right]. \qquad (5)$$

This equation is solved numerically and f is integrated over velocities exceeding the critical velocity to get $n^{\rm hot\text{-}tail}$.

The primary runaway population generated by the Dreicer and hot-tail processes is further amplified by the avalanche mechanism [5]

$$\left(\frac{dn_{\rm run}}{dt}\right)^{\rm avalanche} \simeq n_{\rm run}\frac{E/E_{\rm c}-1}{\tau\ln\Lambda}\sqrt{\frac{\pi\varphi}{3(Z_{\rm eff}+5)}}\left(1-\frac{E_{\rm c}}{E}+\frac{4\pi(Z_{\rm eff}+1)^2}{3\varphi(Z_{\rm eff}+5)(E^2/E_{\rm c}^2+4/\varphi^2-1)}\right)^{-1/2}. \qquad (6)$$

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

The radial diffusion coefficient is given by Rechester-Rosenbluth estimate $D_{RR} = \pi q v_{\parallel} R (\delta B/B)^2$, where q is the safety factor, $v_{\parallel} \simeq c$ is the parallel velocity, R is the major radius and $\delta B/B$ is the normalized magnetic perturbation amplitude. Equations (1), (2) and (3) are solved simultaneously to study plasma shutdown scenarios with neon and argon impurity injection.

We use a specific ITER-like scenario with a plasma current of 15 MA, major radius $R = 6.2$ m, minor radius $a = 2$ m, and magnetic field $B = 5.3$ T. Figure 1 shows the initial plasma temperature, density and current profiles.

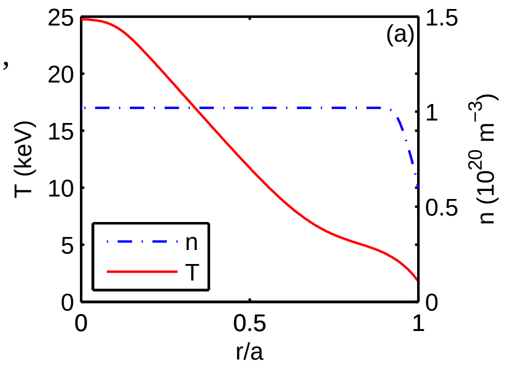

Figure 1: Initial density and temperature profiles as functions of normalized radius r/a

Simulations with different neon and argon concentrations were performed to determine the thermal (τ_{TQ}) and current quench times (τ_{CQ}) and the total runaway current generated. These calculations were done without runaway losses. The current and thermal quench times are defined as the time when the current and thermal energy decrease to 1/e of their original value. Figure 2(a) shows the thermal quench time for different concentrations of neon, argon and a mixture of argon and deuterium (constant $n_D = 10n_0$). Argon radiates much stronger than neon, and therefore the thermal quench time is much shorter. The thermal quench time decreases if the impurity concentration is increased for both impurity types. The argon + deuterium mixture has similar thermal quench times as the pure argon because the argon concentration determines the radiation losses. The current quench times (Fig. 2(b)) have similar tendency as the current quench time. The runaway current is shown on Fig. 2(c). Neon and argon produces significant

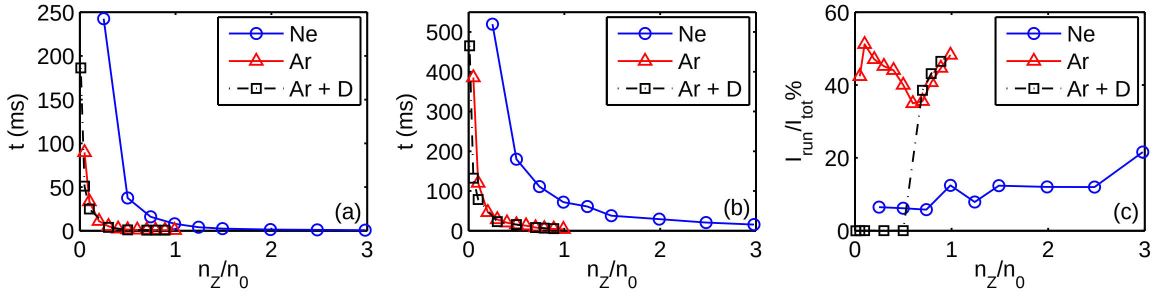

Figure 2: (a) Thermal quench time, (b) current quench time and (c) runaway current that is generated after injection of different amount of neon, argon and a mixture of argon and deuterium ($n_D = 10n_0$) into the plasma

runaway current. The cooling is more effective for argon and the high electric field creates higher runaway current than for neon. If deuterium is added to the argon, the Dreicer generation is suppressed therfore if $n_{\mathrm{Ar}}/n_0 < 0.7$ then there are no runaways produced. At higher argon concentration the hot-tail effect becomes effective which is later on amplified by the avalanche mechanism.

Runaway electron diffusion due to magnetic perturbations can decrease the runaway density. The effect of the magnetic perturbation is studied for the argon scenario $n_{\mathrm{Ar}}/n_0 = 0.9$. Without runaway losses the simulation ends with high runaway current because there is a strong initial seed runaway profile due to the hot-tail effect. The maximum runaway current for different magnetic perturbation levels are compared in Fig. 3. With low magnetic perturbation levels ($\delta B/B < 10^{-4}$) the avalanche mechanism is not suppressed. In this case the runaway profile becomes broader due to the diffusion and therefore the final runaway current is increased. At high magnetic perturbations ($\delta B/B \geq 8\cdot 10^{-4}$) the runaway loss rate is higher than the avalanche rate and the runaway electrons generated by the hot-tail process diffuse out of the plasma before they form a strong runaway beam.

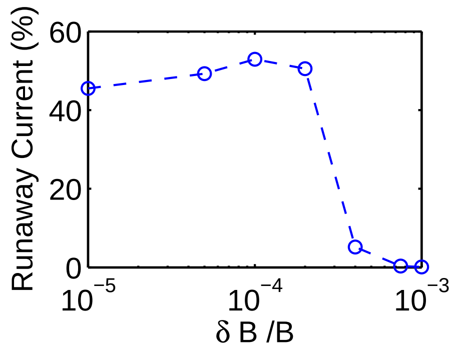

Figure 3: Runaway fraction of total current as a function of magnetic field perturbations at injection of argon ($n_{\mathrm{Ar}}/n_0 = 0.9$).

Our study shows that high neon and argon concentration can cause short thermal and current quench times, but in this case a high runaway current is produced. With lower concentration of impurities this can be avoided, but the inhomogeneities in cooling can also result in a strong runaway generation by the avalanche mechanism. A simple estimate for runaway losses shows that diffusion due to large magnetic perturbations could counteract the avalanche generation.

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