Runaway Electron Generation during Plasma Shutdown by Killer Pellet Injection

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Abstract

Tokamak discharges are sometimes terminated by disruptions that may cause large mechanical and thermal loads on the vessel. To mitigate disruption-induced problems it has been proposed that "killer" pellets could be injected into the plasma in order to safely terminate the discharge. Killer pellets enhance radiative energy loss and thereby lead to rapid cooling and shutdown of the discharge. But pellets may also cause runaway electron generation, as has been observed in experiments in several tokamaks. In the present work, runaway dynamics in connection with killer-pellet-induced fast plasma shutdown is considered. We determine the post-disruption runaway current profile by solving the equation for runaway production coupled to an equation for the evolution of the toroidal electric field. To provide the evolution of the background plasma density and temperature we rely upon a pellet ablation code. In this way we can investigate the effect of varying pellet size, material and injection velocity.

Introduction

Killer pellet injection is a way to avoid disruption related damages, since the kinetic energy of the plasma is then reduced through isotropically distributed impurity radiation. Fast plasma shutdown by killer pellets has been demonstrated in several tokamak experiments [1], and it was shown that significant reduction of the thermal and mechanical loads on the vessel can be achieved. However, as the plasma cools down quickly, a large toroidal electric field is induced which may accelerate some electrons to relativistic energies. These runaway electrons can damage the first wall on impact.

During pellet injection there are two competing effects that may affect runaway generation: the pellet increases the electron density and therefore suppresses acceleration of runaway electrons because of higher collisional friction. But at the same time the pellet also increases the plasma resistivity due to cooling and higher charge number. This leads to an increased toroidal electric field which accelerates the runaways.

In this work we investigate the effect of fast plasma shutdown by deuterium and carbon pellet injection in a JET-like plasma. The evolution of the background plasma density and temperature is calculated by a pellet code [2, 3] describing the ablation of the pellet and the dynamics of the cloud which surrounds it. These complex phenomena are implemented in a Lagrangian code, which describes the hydrodynamic expansion of the cloud along the magnetic field lines including atomic processes in the cloud, the penetration of ambient plasma particles, heat diffusion into the cloud, and the electrostatic shield formation at the cloud periphery. The cross field motion of the pellet is also considered. Knowing the temperature and density variation we then determine the post-disruption runaway current profile by solving the equation for runaway production coupled to an equation for the evolution of the toroidal electric field. We have found that deuterium pellets do not cool the plasma enough for fast current shutdown. Multiple carbon pellet injection may be a promising method for disruption mitigation, and we have determined the size and velocity of the pellets necessary to avoid runaway generation.

Pellet induced cooling

The heat flux carried by hot plasma electrons ablate the injected pellets, and the particles removed from the pellet surface form a cloud which surrounds the pellet. The pellet cloud is heated by the background plasma electrons, and consequently it expands and is ionised due to collisions. In the toroidal direction the expansion is almost free, while the expansion in the poloidal direction is stopped when the ionisation sets in at the cloud periphery (at the cloud radius $R_{\rm cld}$). Both the neutrals and ions of the cloud emit radiation as they are excited by collisions. The ablation and the cloud formation extract energy from the background plasma. In our model, this energy is extracted adiabatically from the plasma between two nearby flux surfaces, separated radially by a distance equal to the cloud diameter, which is about ~ 1 cm. In the following, this volume of plasma will be called the flux-tube.

The heat reaching the pellet cloud is composed of the heat transported to the two ends of the cloud, $Q_\parallel$, and the heat which reaches the lateral surface of the cloud, $Q_\perp$. In a thermal plasma the parallel heat flux $q_\parallel$ can easily be determined by assuming a Maxwellian background plasma [4]. A more difficult task is to estimate the transverse heat flux, $q_\perp$, reaching the cloud periphery, as it depends on the perpendicular heat conductivity, which is the sum of classical, neoclassical and turbulent conductivities. In general the perpendicular heat flux per unit area is much smaller than parallel one. On the other hand the heat reaching the pellet cloud is determined not only by the heat flux but also by the surface area which the flux crosses: $Q_\perp/Q_\parallel = (q_\perp/q_\parallel)(2z_{\rm cld}/R_{\rm cld})$, where $z_{\rm cld}$ is the length of the cloud in toroidal direction.

In the case of deuterium pellets, the cloud length is comparable to its radius [5], so the heat absorption on the lateral surface of the cloud can be neglected. However, the length of an *impurity* pellet cloud is an order of magnitude higher than its radius [2, 6], so the heat absorption reaching the lateral surface of the cloud should be considered, although the perpendicular heat flux is smaller than the parallel one. Thus for impurity pellets we need to take into account not only the heat flux reaching the two toroidal ends, but also the perpendicular flux reaching the lateral part. As we do not know the exact value of the perpendicular heat conductivity, we assume that the perpendicular heat flux is 5% of the free parallel energy flux $q_\parallel$, which in Ref. [7] was found to agree with experimental and numerical results.

As a result of the total heat absorption the temperature of the flux tube, $T_{\rm e}$, is reduced. The temperature reduction is calculated by the pellet code in a self-consistent way according to the energy balance equation

$$\frac{3}{2}n_{\rm bg}T_{\rm e}(t+dt)(V_{\rm flt}-V_{\rm cld}(t+dt))=\frac{3}{2}n_{\rm bg}T_{\rm e}(t)(V_{\rm flt}-V_{\rm cld}(t))-q_{\parallel}\pi R_{\rm cld}^2(1+Q_{\perp}/Q_{\parallel})dt, \quad (1)$$

where dt is the time step and $V_{\rm flt}$ and $V_{\rm cld}$ are the volumes of the flux-tube and of the pellet cloud respectively. Here we assumed that the cold electrons are trapped in the cloud by an electrostatic potential so they do not modify the number of background electrons $n_{\rm bg}$. Furthermore we assume that the plasma cools uniformly on a given flux surface.

Both the background and cloud electrons can be considered as thermal electrons, thus in the present study we will not distinguish these two populations and the density increase will be estimated simply by summing up the number of the electrons neglecting their temperature difference.

In the case of impurity pellet injection the effective ion charge $Z_{\rm eff}$ increases, while for deuterium pellets the assumed $Z_{\rm eff}=1$ is unchanged. Regarding the determination of $Z_{\rm eff}$ the same assumption has been done as in the case of electron density determination. The number of different ions species of the cloud are added to the number of hydrogen ions in the flux tube and $Z_{\rm eff}$ is calculated accordingly: $Z_{\rm eff}=(n_{\rm D}+\sum_{i=1}^{Z}n_i i^2)/n_{\rm e}$, where $n_{\rm D}$ denotes the density of deuterium, n_i the density of each charge state i, Z is the charge number and $n_{\rm e}$ is the sum of the cloud and background electron densities.

Runaway production

If the pellet induced cooling is very efficient, the rising toroidal electric field E may become higher than the critical electric field $E_{\rm c}=m_{\rm e}c/(e\tau)$, where $\tau=4\pi\varepsilon_0^2m_{\rm e}^2c^3/(n_{\rm e}e^4\ln\Lambda)$. When this happens, runaway electrons can be produced by the primary (or Dreicer) mechanism at the rate [8]

$$\dot{n}_{\rm run}^{\rm I}\simeq\frac{n_{\rm e}}{\tau}\left(\frac{m_{\rm e}c^2}{2T_{\rm e}}\right)^{3/2}\left(\frac{E_{\rm D}}{E}\right)^{3(1+Z_{\rm eff})/16}\exp\left(-\frac{E_{\rm D}}{4E}-\sqrt{\frac{(1+Z_{\rm eff})E_{\rm D}}{E}}\right), \quad (2)$$

where $E_{\rm D}=m_{\rm e}^2c^3/(e\tau T_{\rm e})$ is the Dreicer field. For simplicity, in this work we neglect the "burst" of runaway production caused by incomplete thermalisation of fast electrons due to rapid cooling of the bulk plasma [9]. Previous pellet injection simulations [10, 11], showed that the burst mechanism can be more efficient than Dreicer generation unless there are large and rapid losses of fast electrons. A satisfactory treatment of the burst effect would extend the model of the dynamics from the two dimensions radius and time to include at least one velocity dimension, which is beyond the scope of the present work.

Once primary runaways are generated they act as a seed for the secondary avalanche mechanism, with the production rate [12]

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

where $\varphi=1-1.46\epsilon^{1/2}+1.72\epsilon$, and $\epsilon=r/R$ is the inverse aspect ratio. The evolution of the electric field is governed by the parallel component of the induction equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E}{\partial r}\right) = \mu_0 \frac{\partial}{\partial t}\left(\sigma_{\parallel} E + n_{\rm run} e c\right), \tag{4}$$

where $\sigma_{\parallel} = \sigma_{\parallel}(T_{\rm e}, Z_{\rm eff}, \epsilon)$ 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. When the initial current is known and $n_{\rm e}(r,t)$, $T_{\rm e}(r,t)$ and $Z_{\rm eff}(r,t)$ have been determined by the pellet code, Eqs. (2–4) are solved numerically to give the resulting runaway production and the evolution of the electric field [13].

Mitigation

For a fast enough plasma shutdown, the current decay time should be less than the time constant for plasma equilibrium control. The current decay time can be estimated to be $\tau_{\rm d} \simeq \sigma_{\parallel}\mu_0 a^2$, where a is the minor radius of the device. The current quench time, $\tau_{\rm d}$, should be at most of the order of 1 s in ITER [14] and considerably shorter in JET [15] in order to avoid large halo currents in the vessel. In practice, this means that for efficient shutdown of the plasma current the plasma has to be cooled down to a few hundred eV. If the temperature becomes too low and the density is not sufficiently increased, a seed of runaways can be produced by the Dreicer mechanism. Close to the plasma edge where the volume of a flux tube is very large, the cooling is not as strong as in the plasma center where the flux tubes are small. This means that the runaway seed becomes largest roughly at the radius corresponding to the pellet penetration depth. If the temperature remains high inside this radius during the current quench, the electric field will diffuse inwards, passing the seed region, where it amplifies the runaway population through secondary generation. It is therefore desirable to cool down the plasma to a rather uniform temperature profile of a few hundred eV in order to avoid the runaways and to make it possible for the thermal quench to be followed by sufficiently fast current quench.

In our calculations we use the following initial temperature and density profiles, characteristic for a JET-like plasma: $T_{\rm e}^{\rm initial} = T_0(1-0.75\rho^2)^2$, with $T_0 = 3.1$ keV, and $n_{\rm e}^{\rm initial} = n_0(1-0.9\rho^2)^{2/3}$, with $n_0 = 2.8\cdot 10^{19}$ m^{-3}, where $\rho = r/a$ is a normalised plasma radius.

First, the temperature decrease and density increase induced by deuterium pellets injected from the low field side were calculated. For deuterium pellets, the ionised cloud formation is preceded by a spherically expanding neutral cloud, which has a shielding effect that is taken into account [3]. Figure 1 shows a simulation of successive injection of three hydrogen pellets with $r_{\rm p} \approx 3$ mm and $v_{\rm p} = 160$ m/s [16]. The pellet parameters were chosen to give deep penetration and large cooling. As the ionised cloud of one deuterium pellet is relatively small, the local cooling is of the order of 100 eV. On the other hand, the ablation rate and the number of the ablated particles is high since the evaporation energy of deuterium is extremely small (0.005 eV). As the plasma temperature (which mainly determines the ablation) does not change considerably and the density is strongly increased, the next pellet which enters the plasma will have almost the same penetration depth as the previous one. The drastically increased density in Fig. 1 is beneficial for runaway mitigation, but the small cooling effect of each pellet leads to the conclusion that very many pellets are needed for fast plasma current shut down.

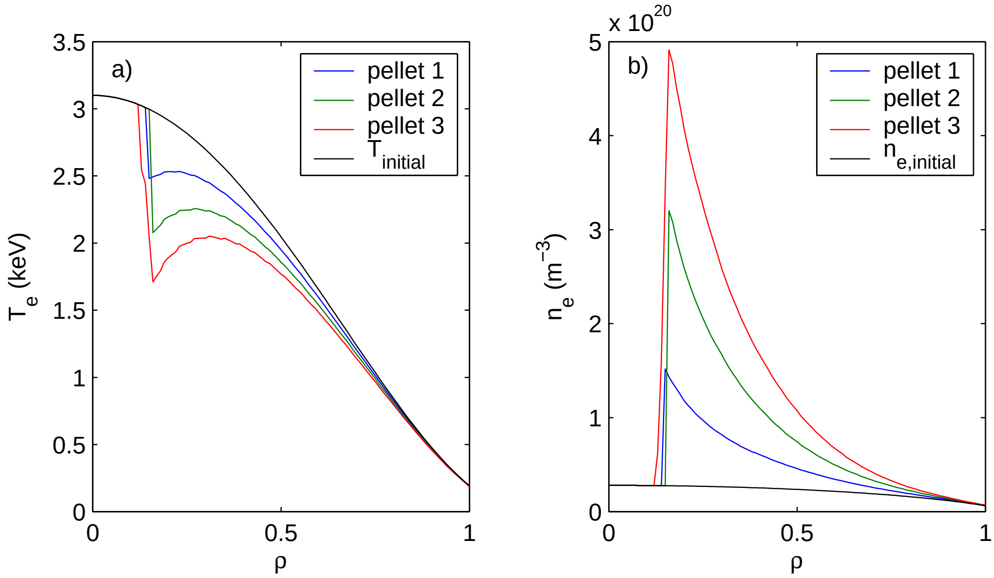

Figure 1: *Simulations of the electron temperature (a) and density (b) after injection of three successive* $r_{\rm p} = 3$ mm, $v_{\rm p} = 160$ m/s *hydrogen pellets.*

Second, the cooling and density increase induced by single carbon pellets of various sizes and velocities have been calculated. The evaporation energy of carbon is at least two orders of magnitude higher than for deuterium (we assume 4 eV). For given plasma parameters, the pellet size and velocity determine the penetration depth, and the region which is cooled by the pellet. The simulation shows that the cooling is determined mainly by the pellet velocity, i.e. the time which the pellet spends in a given flux tube, and the penetration depth is determined mainly by the pellet size, see Fig. 2. This is true also for deuterium pellets. In the case of low velocity (100 m/s) and big pellets ($r_{\rm p} \approx 0.8-0.9$ mm) runaways are induced, see Fig. 3. Most runaways are in this case generated by the secondary mechanism. For medium and high velocities, of the order of $200 - 1000$ m/s, the pellet penetrates to the center (or even beyond), and no runaways are produced. The pellets cool down the plasma and trigger a current quench, but for single pellet injection the current decay time is too long (> 10 s).

To shorten the current quench time, multiple pellet injection is necessary, where the plasma is cooled in consecutive sequences. Similarly to single pellet injection, slow pellets (100 m/s) will induce runaways, even if the size of the pellets is small. Big single pellets with medium velocity (200 m/s) do not cool the plasma enough for fast plasma shutdown (neither do they produce runaways). However, multiple medium size pellets having the same velocity, penetrate far into the plasma and cause a considerable cooling. It is shown in Fig. 4a that the last in a series of four $r_{\rm p} = 0.5$ mm, $v_{\rm p} = 200$ m/s pellets reaches as far as $\rho = 0.05$ and cools the plasma to around 400 eV. It is a difficult task to model the

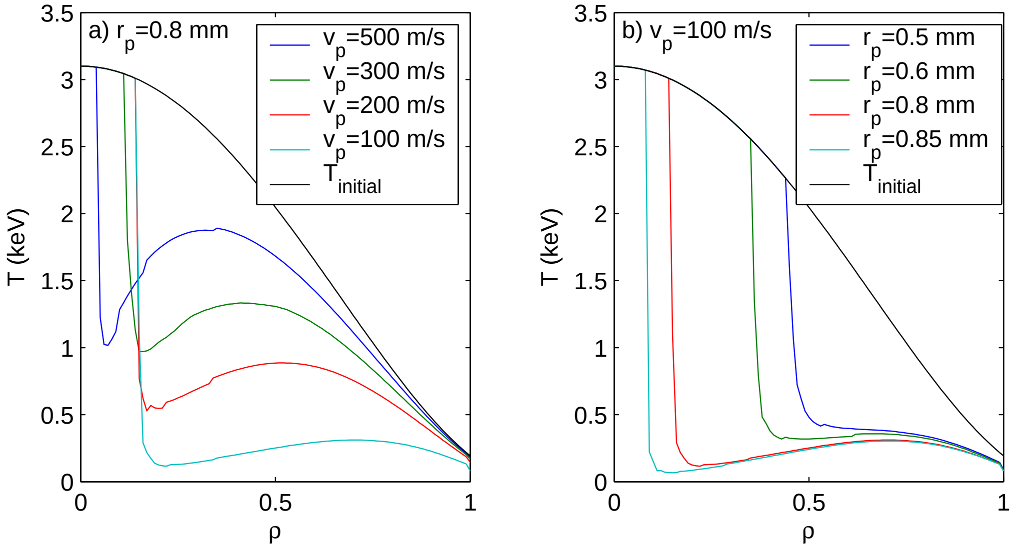

Figure 2: *Simulations of cooling due to single carbon pellet injection. a) Pellets with* $r_{\rm p} = 0.8$ mm *and different velocities. b) Pellets with* $v_{\rm p} = 100$ m/s *and different radii.*

transport in the central plasma after the injection of the four pellets. We have assumed that the density and temperature quickly become constant and equal to the average value for $\rho < 0.1$ as soon as the last pellet enters this region. This enables the calculation of the current evolution in Fig. 4b. The current quench time is around 2 s and only a small runaway current of less than 0.1% of the initial current is produced. However, to get down to a quench time below 1 s one needs to cool more, and a sophisticated tailoring of the final temperature profile using multiple individually different pellets is needed to avoid runaway production.

Conclusions

The ablation of deuterium and carbon pellets injected in JET plasma in order to radiatively dissipate the plasma energy has been calculated by a hydrodynamic code. Our calculations show that low Z impurities such as carbon can be used for mitigation purposes if they are injected with medium size velocity. To avoid runaways, the slowest pellet which may be used has a velocity of $150 - 200$ m/s. Multiple injection of large pellets with medium velocities is found to be a promising mitigation method. However, it is difficult to cool the plasma enough to get a satisfactorily short current decay time without causing runaway production. A $\tau_{\rm d}$ of around 2 s was obtained in the simulations, which is too long, at least for JET-like plasma.

Previous theoretical work suggested that injection of high-Z impurities in plasmas will result in large number of runaways [17]. Therefore, it has been suggested that disruption mitigation should be achieved by a massive injection of low-Z material such as D or He. Our work shows that many D pellets will be needed in order to produce enough cooling.

In the future it would be interesting to perform numerical simulations with carbon-

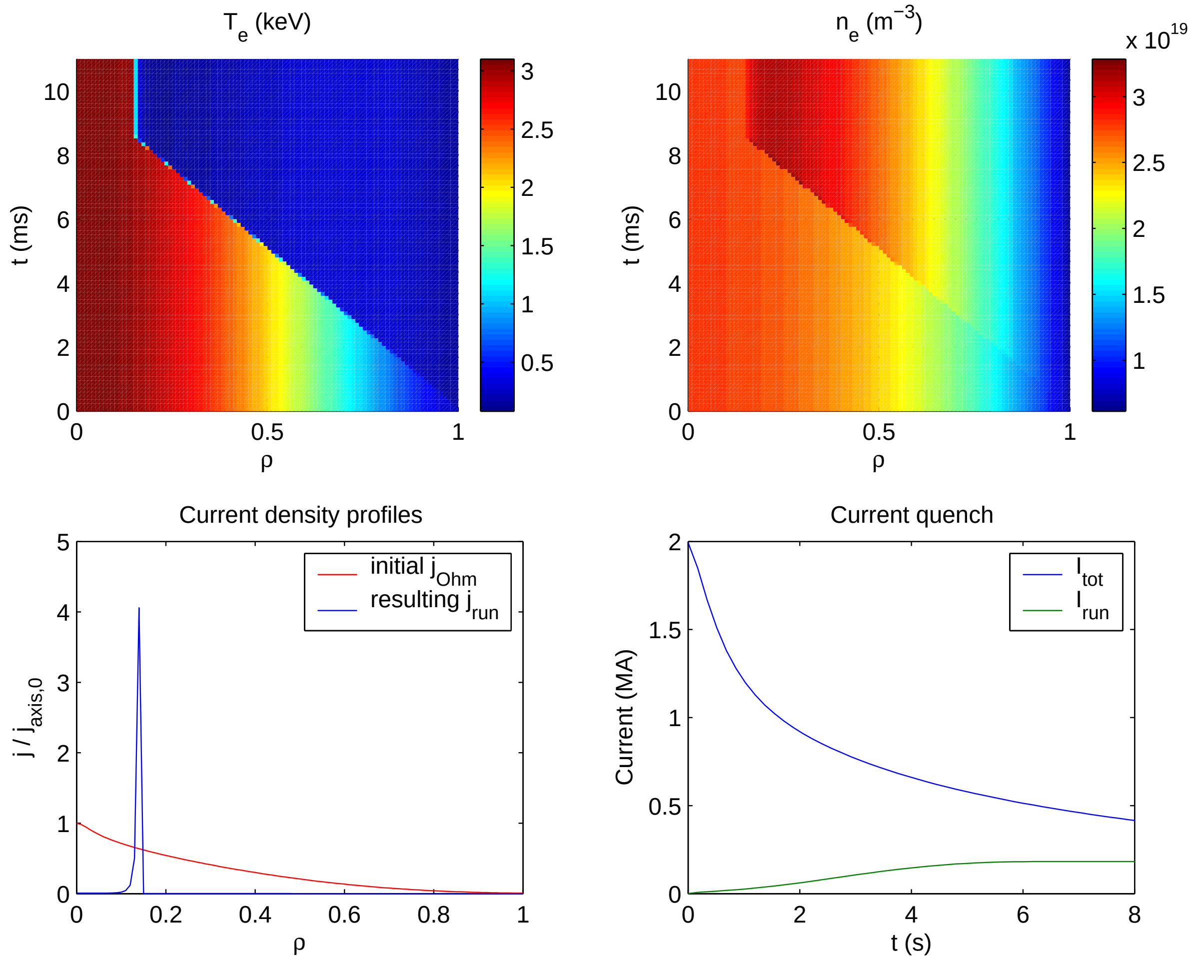

Figure 3: *A simulation of a carbon pellet with* $r_p = 0.8$ mm *and* $v_p = 100$ m/s *Top: The evolution of the temperature and density, calculated by the pellet code. The density increase is too small to compensate for the temperature drop, so Dreicer runaways will initially be generated. Bottom left: The initial radial profile of the Ohmic current density and the post-disruption runaway current density. Bottom right: The total current falls on a slow time scale of several seconds, which gives the avalanche mechanism time to produce a considerable runaway current.*

doped deuterium pellets. Doped-pellet calculations have been performed in Ref. [18], where simulations of the injection of a rapid series of 30-45 deuterium pellets doped with a small concentration of krypton has shown that fast shutdown can be achieved without large runaway generation. However, the model used in Ref. [18] does not include the dynamics of the radial distribution of the current and the electric field, which is important especially for secondary runaway generation.

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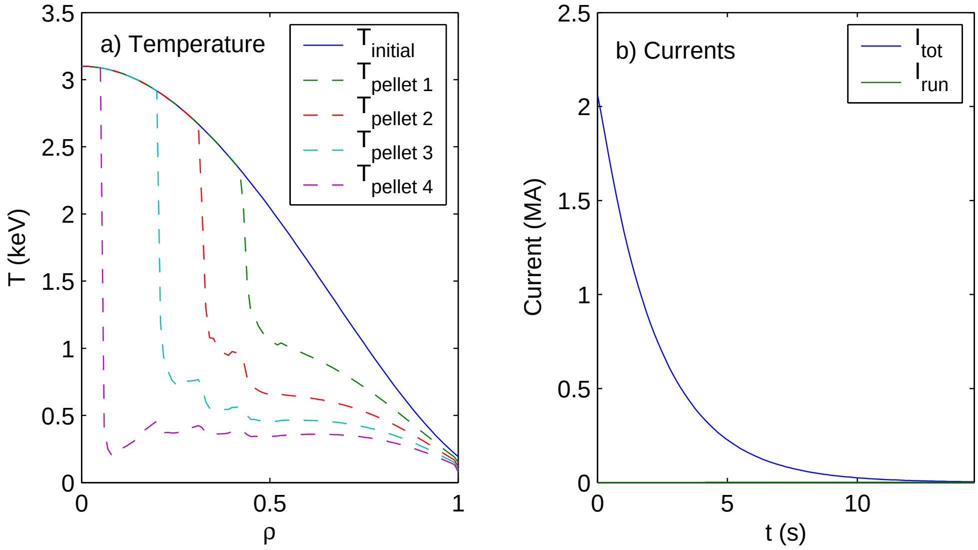

Figure 4: *a) The simulated temperature after injection of four successive carbon pellets with* $r_\mathrm{p} = 0.5$ mm *and* $v_\mathrm{p} = 200$ m/s. *b) The resulting current quench. The final* I_run *is less than* 0.1% *of the initial current.*

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