Runaway Electron Beam Dissipation in Tokamak Disruptions

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1. Introduction Disruption generated runaway electrons (REs) pose a significant challenge for the operation of next-step devices like ITER. Several control and mitigation schemes are currently under investigation, with the enhanced loss of the runaway current observed when injecting high-Z impurities by means of Massive Gas Injection (MGI) or Shattered Pellet Injection (SPI) being especially promising. In this paper, the dissipation and decay of the runaway current during disruptions is investigated. Energy losses due to the collisions of the runaway electrons with the background plasma particles will be considered. The effects on the generation of the runaway current during the current quench (CQ) phase of the disruption, as well as the mitigation of already formed plateau runaway beams will be analyzed.

2. Energy dissipation The starting point is the assumption that the dissipation of the runaway current is determined by the time at which the accelerating electric field drops below the threshold electric field for runaway generation. Hence, if $F_0(E)$ is the initial ($t = 0$) runaway energy distribution function, the current at time t will be

$$I_r(t) = \int_{E_0}^{E_0^{max}} F_0(E)\, dE \Longrightarrow \frac{dI_r}{dt} = -\frac{dE_0}{dt} F_0(E_0), \tag{1}$$

where E_0^{max} is the maximum runaway energy at the start of the decay ($t = 0$) and E_0 is the electron energy dropping to zero after time t, which is determined by the RE energy dynamics, $dE/dt = U(E,t)$, so that the distribution function at t is given by

$$F(E,t) = F_0\left(E - \int_0^t U(E',t')\, dt'\right). \tag{2}$$

We focus in this paper on the effect of the collisional losses on the decay of the runaway current. In this case, the runaway energy equation can be simplified to

$$\frac{dE}{dt} \approx ec\left(E_{||} - E_R\right) \tag{3}$$

($E_R = n_e e^3 \ln\Lambda / 4\pi\varepsilon_0^2 m_e c^2$ is the critical field for runaway generation [1]) and Eq. (3) can be easily solved yielding

$$E(t) \approx E_0 + \int_0^t ec\,(E_{||} - E_R)\, dt', \tag{4}$$

so that the energy E_0 which decays to zero at time t would be

$$E_0 \approx -\int_0^t ec\,(E_{||} - E_R)\, dt'. \tag{5}$$

The resulting runaway current decay rate [Eq. (1)], assuming the initial RE distribution determined by the avalanche process, $F_0(E) \approx (I_r^0/T_r) \cdot e^{-E/T_r}$ [$I_r^0 \equiv I_r(t=0)$, $T_r = m_e c^2 \ln\Lambda\, a(Z_{eff})$, and $a(Z_{eff}) \approx \sqrt{3\,(5+Z_{eff})/\pi}$], is

$$\frac{dI_r}{dt} \approx -\frac{dE_0}{dt}\, F_0\left(-\int_0^t ec\,(E_{||}-E_R)dt'\right) \approx \frac{ec\,(E_{||}-E_R)\, I_r^0}{T_r}\, e^{\frac{\int_0^t ec\,(E_{||}-E_R)\,dt'}{T_r}}$$
$$= \frac{ec\,(E_{||}-E_R)}{T_r}\, I_r, \qquad (6)$$

where $I_r(t) = \int_{E_0}^{E_0^{max}} F_0(E)\, dE \approx I_r^0\, e^{\frac{\int_0^t ec\,(E_{||}-E_R)\,dt'}{T_r}}$ has been used, and

$$F(E,t) = F_0\left(E - \int_0^t ec\,(E_{||}-E_R)\,dt'\right) \approx \frac{I_r(t)}{T_r}\, \exp\left(-\frac{E}{T_r}\right). \qquad (7)$$

Thus, the distribution function keeps the avalanche like shape, which is the result of including the collisional losses alone, neglecting the electron radiation. Finally, the RE beam kinetic energy, W_{kin}, can be obtained as

$$\Delta W_{kin} \approx 2\pi R_0 \int_0^t (E_{||}-E_R)\, I_r\, dt$$
$$\approx 2\pi R_0\, I_r^0 \int_0^t (E_{||}-E_R)\, e^{\frac{\int_0^{t'} ec\,(E_{||}-E_R)\,dt''}{T_r}}\, dt' = \frac{2\pi R_0\, T_r}{ec}\,(I_r - I_r^0). \qquad (8)$$

Hence, W_{kin} decreases at the same rate that I_r decays.

3. CQ dissipation and RE plateau mitigation The effect of the collisional dissipation during the formation of the runaway beam in a tokamak disruption is illustrated in Fig. 1 (left) which shows the RE current evolution during the CQ phase of a 15 MA disruption in ITER. The simulation has been carried out using a simple zero dimensional tokamak disruption model, including the replacement of the plasma current by the RE current, $E_{||} = \eta\,(j_p - j_r)$ [$j_{p,r} = I_{p,r}/\pi a^2$ are the average plasma and runaway current densities, respectively, and a the plasma minor radius]. The total current I_p is calculated according to $dI_p/dt = -(2\pi R_0/L) \cdot E_{||}$ ($R_0 \sim 6.2$ m is the major radius and $L \sim 5\,\mu$H the internal plasma inductance), and the generation of the runaway current is assumed to take place by the avalanche amplification of an initial runaway seed current, I_{seed}. The exponential current quench time ($\tau_{res} \equiv L/R_p = L\,a^2/2\,R_0\,\eta$; η is the plasma resistivity) ~ 50 ms, $Z_{eff} = 3$, $I_{seed} = 10^{-3}$ MA, and $n_e = 5 \times 10^{21}\,\mathrm{m}^{-3}$. Only collisions with the free electrons are considered. Initially, as illustrated in the right figure (dashed line) $E_{||} \gg E_R$ and runaway current is generated due to the avalanche mechanism. However, the formation of the runaway current leads to the decrease of the electric field and, when $E_{||} = E_R$, the runaway avalanche is stopped, I_r reaches a maximum (~ 6 MA) and starts to decay. Once $E_{||} < E_R$, the current decays following a marginal stability scenario [2] in which the electric field remains close to (but smaller than) E_R (dashed line in right figure), yielding a linear decay of the plasma current ($dI_p/dt \propto E_{||} \sim E_R$). The figure to the right also shows the time evolution of $E_{||}$ for disruption CQs under the same conditions but $n_e = 10^{21}$ and $10^{22}\,\mathrm{m}^{-3}$. When the amount of dissipation (E_R) is large enough (high density, $n_e = 10^{22}\,\mathrm{m}^{-3}$ in the figure), the evolution of the plasma and RE current

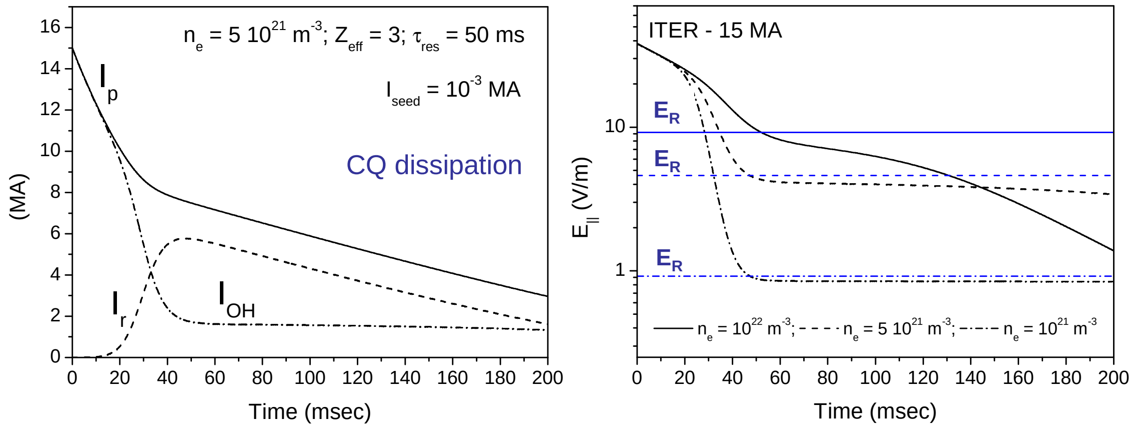

Figure 1: For the CQ of a 15 MA disruption in ITER with $\tau_{res} = 50\,\mathrm{ms}$ and $I_{seed} = 10^{-3}$ MA: Left: Time evolution of the plasma current, ohmic (OH) current and RE current for $n_e = 5 \times 10^{21}\,\mathrm{m}^{-3}$; Right: Time evolution of the electric field for $n_e = 10^{21}$, 5×10^{21} and $10^{22}\,\mathrm{m}^{-3}$. The values of E_R for the three cases (horizontal lines) are indicated.

during the decay can depart from the marginal stability condition, and the values of $E_{||}$ fall well below E_R.

The effectiveness of collisional dissipation in ITER during the CQ is limited by the range of τ_{res} values that are acceptable for tolerable mechanical loads onto the vessel and in-vessel ITER components ($\sim 22 - 66\,\mathrm{ms}$). This restricts the amount of impurities that can be injected before the thermal quench so that RE plateau currents of several MAs may occur for this τ_{res} range. In such a case, a second mitigation scheme has to be in place for the dissipation of the generated RE current. An example is illustrated in the left Fig. 2 corresponding to the mitigation of a 10 MA RE plateau in ITER by raising the density to $n_e = 5 \times 10^{21}\,\mathrm{m}^{-3}$. The sudden increase in E_R leads to the drop of I_r which results in a large induced electric field and the replacement of the RE current by ohmic current during the current decay.

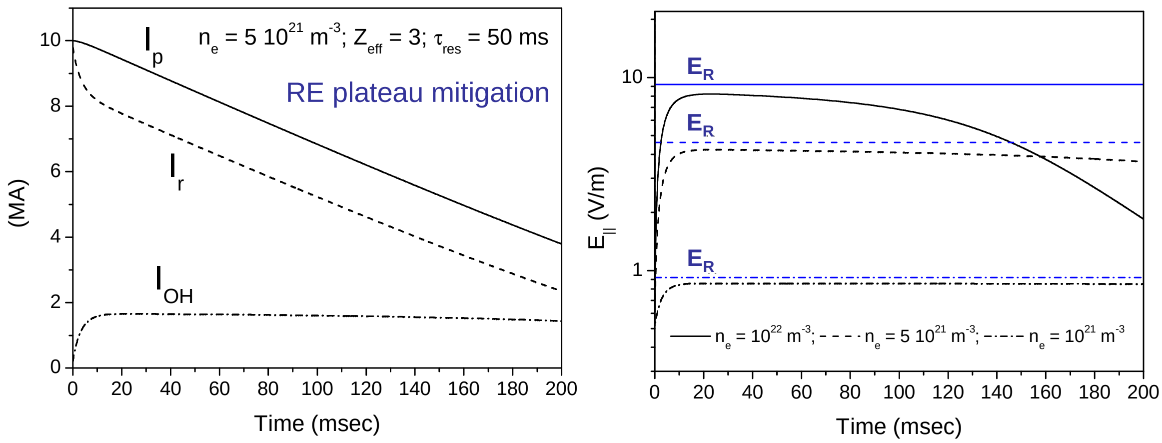

Figure 2: Mitigation of a 10 MA RE plateau in ITER: Left: Time evolution of the plasma current, OH current and RE current for $n_e = 5 \times 10^{21}\,\mathrm{m}^{-3}$; Right: Time evolution of the electric field for $n_e = 10^{21}$, 5×10^{21} and $10^{22}\,\mathrm{m}^{-3}$.

Fig. 2 (right) compares the evolution of $E_{||}$ during the mitigation phase for three different n_e. $E_{||}$ rapidly increases to values close to E_R, reaching near threshold marginal stability conditions. Again, when the dissipation (density) is large enough, $E_{||}$ cannot rise so close to E_R, and the current decay departs from the marginal stability scenario.

Fig. 3 illustrates the effect of Ar and Ne injection on the mitigation of a RE plateau of 10 MA in ITER. The left figure shows the predicted RE current after 100 ms ($\sim$ the expected time in ITER for the vertical instability growth) as a function of the amount of impurities injected (assuming 100% injection efficiency). The plateau RE kinetic energy is 20 MJ (average RE energy $\sim$ 15 MeV) and the collisions with the free and bound electrons of the impurities have been included in the friction force, $E_R \approx e^3 \left(n_{ef}\ln\Lambda_{ef} + n_{eb}\ln\Lambda_{eb}\right)/4\pi\varepsilon_0^2 m_e c^2$ (n_{ef}, n_{eb}: free and bound electron densities; $\ln\Lambda_{ef}$, $\ln\Lambda_{eb}$: Coulomb logarithms for the collisions with free and bound electrons). The figure shows that, for the same amount of impurities, Ar is more efficient than Ne due to its higher atomic number, and indicates that $\sim 5\,\mathrm{kPa}\cdot\mathrm{m}^3$ could be enough for an efficient collisional dissipation of the RE beam, with smaller amounts required for lower RE currents (5 MA in the figure). The figure to the right shows that in the cases of strong dissipation the current decay tends to depart from the marginal stability behavior.

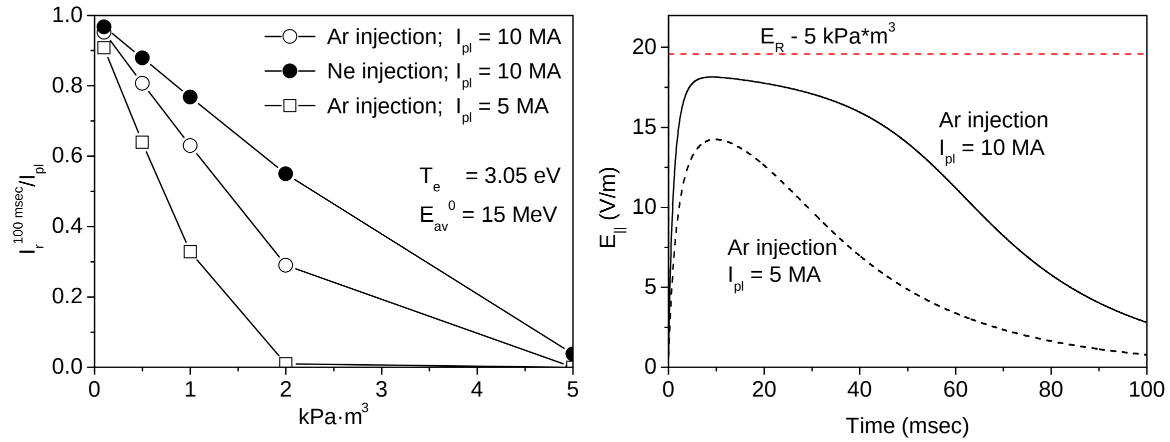

Figure 3: Dissipation of a 10 MA RE plateau by Ar and Ne injection in ITER: Left: Predicted runaway current at 100 ms, normalized to the plateau current, vs. the amount of injected impurities; Right: Comparison between the electric field evolution during the current decay for 5 and 10 MA plateau currents and $\sim 5\,\mathrm{kPa}\cdot\mathrm{m}^3$ Ar injection.

These results suggest that injection of Ar during RE plateau might be a promising scenario for RE dissipation during disruptions if an amount $\sim 5\,\mathrm{kPa}\cdot\mathrm{m}^3$ could be efficiently delivered into the plasma.

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References

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