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The evolution of the plasma current during tokamak disruptions

P. Helander[1], F. Andersson[2], L.-G. Eriksson[3], D. Anderson[2], and M. Lisak[2]

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre,Abingdon, U.K.*

[2]*Dept of Electromagnetics, Chalmers University of Technology, Göteborg, Sweden*

[3]*Association EURATOM-CEA sur la Fusion, CEA Cadarache, France*

Abstract

In a tokamak disruption, the Ohmic plasma current is partly replaced by a current carried by runaway electrons. This process is analysed by combining the equations for runaway electron generation with Maxwell's equations for the evolution of the electric field. This allows a quantitative understanding to be gained of runaway production in present experiments, and extrapolation to be made to ITER. The runaway current typically becomes more peaked on the magnetic axis than the pre-disruption current. In fact, the central current density can rise although the total current falls, which may have implications for post-disruption plasma stability. Furthermore, it is found that the runaway current easily becomes radially filamented due to the high sensitivity of the runaway generation efficiency to plasma parameters.

Introduction

One of the main concerns for a next-step tokamak is the occurrence of disruptions wherein massive amounts of runaway electrons are generated. The fraction of the plasma current that is converted to runaways is about a half in JET and is thought to be larger in ITER due to the high efficiency of runaway "avalanching" when the plasma current is large [1]. Although runaway electrons have been observed for several decades in experiments and much theoretical effort has been devoted to clarifying the physics of how they are accelerated, the problem of actually calculating the runaway current and its profile in a tokamak disruption has received relatively little attention. This is the aim of the present work, where we model the evolution of the toroidal electric field and plasma current (Ohmic + runaway) following the thermal quench of a tokamak disruption [2]. This is done by calculating the runaway current profile $j_r(r,t)$ self-consistently with the toroidal electric field E obtained from the induction equation

$$\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial E}{\partial r} = \mu_0\frac{\partial}{\partial t}\left(\sigma E + j_r\right). \qquad (1)$$

Here, the neoclassical electrical conductivity $\sigma(r,t)$ is a prescribed function of radius and time and is taken to fall dramatically in the thermal quench of the disruption. The runaway current is calculated by Monte Carlo simulation using the ARENA code [3], which solves the relativistic electron kinetic equation in toroidal geometry and couples the solution to Eq. (1). Alternatively, the runaway current can be obtained more approximately by assuming that all runaways travel at the speed of light, $j_r = -n_r ec$, and the runaway density increases as the sum of primary (Dreicer) and secondary (avalanche) generation,

$$\frac{\partial n_r}{\partial t} = \frac{n_e}{\tau}\left(\frac{m_e c^2}{2T_e}\right)^{3/2}\left(\frac{E_D}{E}\right)^{3/8}\exp\left(-\frac{E_D}{4E}-\sqrt{\frac{2E_D}{E}}\right)+\left(\frac{\pi}{2}\right)^{1/2}\frac{n_r(E/E_c-1)}{3\tau\ln\Lambda}, \qquad (2)$$

where $\tau = 4\pi\varepsilon_0^2 m_e^2 c^3/n_e e^4 \ln\Lambda$ is the relativistic electron collision time, $E_D = m_e^2 c^3/e\tau T_e$ the Dreicer field, and $E_c = m_e c/e\tau$ is the relativistic cut-off field below which no runaway generation can occur. Primary runaway generation occurs because of velocity-space diffusion of electrons into the runaway region, while the secondary mechanism is the result of collisions at close range between existing runaways and thermal electrons.

Numerical results

Figure 1 shows output from a typical ARENA simulation of an ITER disruption, where the temperature was taken to fall from an initially peaked profile $T_0 = 22$ keV $\cdot\,(1-0.9x)$, where $x = r/a$ is the normalized radius and $a = 2.5$ m, to a flat post-disruption temperature $T_1 = 5$ eV, according to $T_e(x,t) = T_1 + [T_0(x) - T_1]e^{-t/t_0}$. The initial plasma current was I_p = 15 MA, the density $n_e = 1.1\cdot 10^{20}$ m$^{-3}\cdot(1-0.99x^2)^{0.1}$, and the cooling time $t_0 = 0.5$ ms. The rising runaway current limits the growth of the electric field at $t \simeq 4$ ms, which subsequently decays on a time scale set by the avalanche growth time and the skin time. At the end of the simulation, about two thirds of the pre-disruption current has been replaced by runaway electrons, mostly produced through avalanching. Note that the runaway current evolves to a profile that is much more peaked than the pre-disruption current. This can be understood as a result of the interplay between runaway generation and radial diffusion of the electric field. Because of the peaked temperature profile, runaway generation is most efficient in the centre of the plasma and the rising runaway current therefore limits the electric field relatively early near the magnetic axis. This leads to a hollowing of the electric field profile, which causes additional electric field to diffuse into the centre and even more generation to occur in this region. In the low-temperature plasma after the thermal quench, the resistive diffusion time scale is comparable to the growth time of the runaway avalanche, so that the electric field diffuses radially at the same time as it generates runaways.

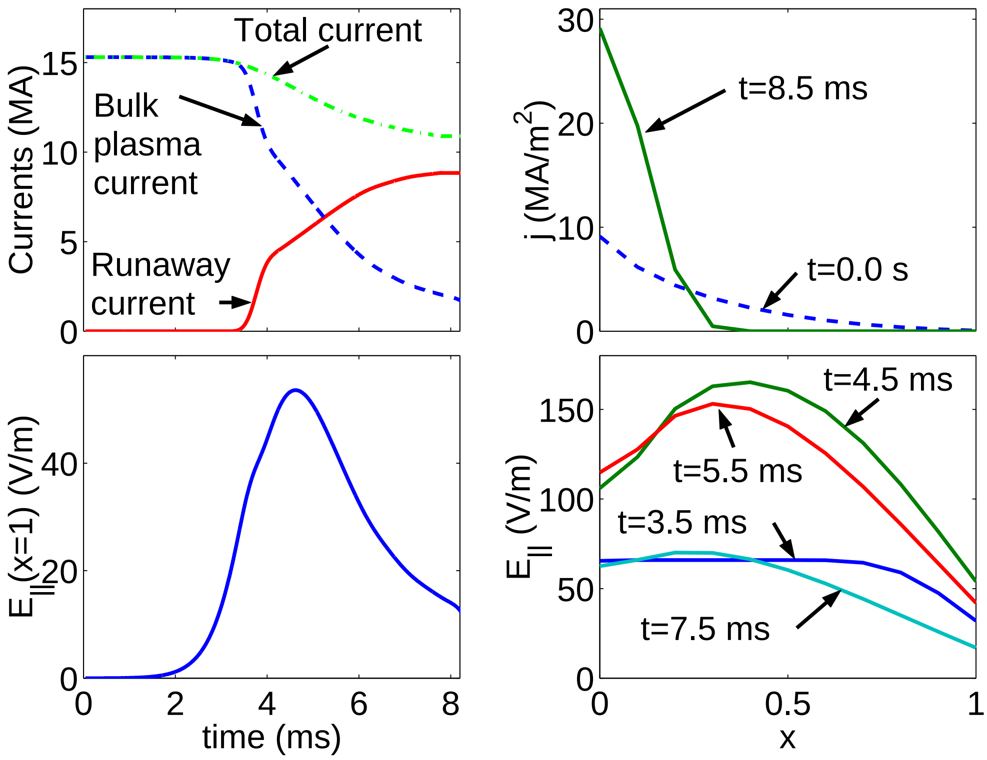

Figure 1: ARENA *simulation of the runaway dynamics in an ITER disruption.*

Figure 2 shows the result of solving Eqs (1) and (2) for parameters appropriate to a typical JET disruption. About half the pre-disruption current is converted to runaways, whose radial profile is again peaked on the magnetic axis. The generation of runaway electrons occurs in two stages, with a quick burst of Dreicer generation acting as a seed for a slower subsequent avalanche of secondary runaways. Most runaways are produced by this secondary mechanism. The results are very similar to both the corresponding ARENA simulation (not shown) and to experiment: the current conversion efficiency is about a half, the time scale is a few ms, and the current density increases on axis.

Primary runaway production, which is described by the first term on the right-hand side of Eq. (2), is very sensitive to plasma paramaters. Any slight variation in the electron temperature or density between neighbouring flux surfaces therefore causes the seed runaway population to vary rapidly with radius. This variation is amplified by the avalanche and reflected in the final current profile, as illustrated in Fig. 3. Here, the same parameters were used as in Fig. 2, except that the cooling time was taken to vary sinusoidally by 10% across the plasma, $t_0 = 0.1\,\mathrm{ms}\cdot[1+0.1\sin(40\pi x)]$. Such variation could result from a thermal instability in the cooling plasma. This does not affect the overall conversion efficiency from Ohmic current to runaway current, but the latter acquires huge radial variations. This may explain why X-rays emitted by runaway electrons hitting the first wall are usually emitted in a series of sharp bursts.

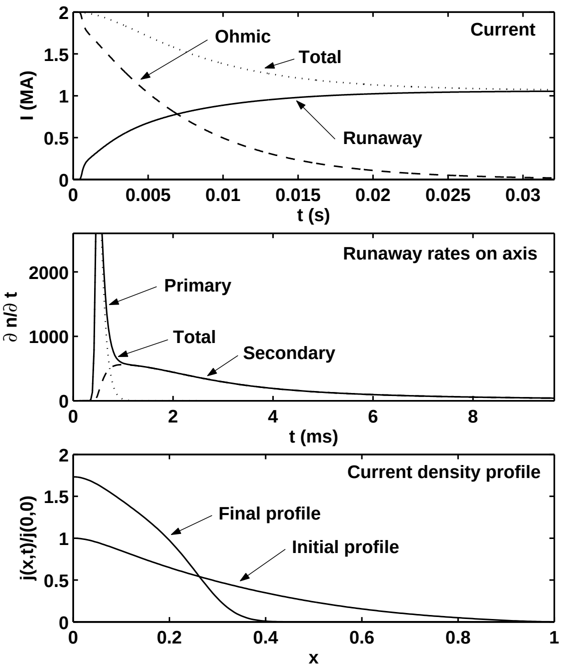

Figure 2: *Numerical solution of Eqs. (1) and (2) for JET parameters:* I_p *= 2 MA,* $n_e = 5\cdot 10^{19}\,m^{-3}\cdot(1-0.9x^2)^{1/2}$, $T_0 = 1.4\,keV\cdot(1-0.9x^2)^2$, $T_1 = 10\,eV$, $x = r/(1\ m)$, $t_0 = 0.1\,ms$.

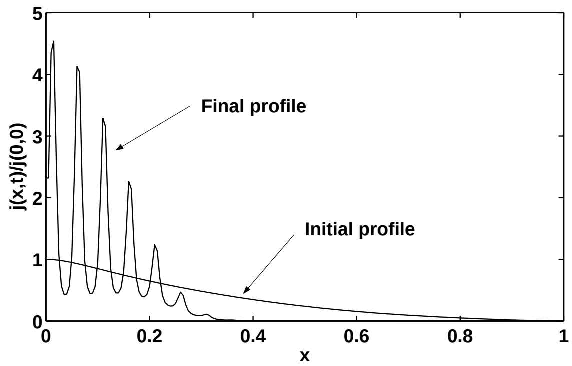

Figure 3: *Same as Fig. 2 but with the cooling time* t_0 *varying sinusoidally with radius by 10%.*

A more detailed account of these results can be found in Ref. [2], where their main features are also explained analytically.

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