Predictions on runaway current and energy during disruptions in tokamak plasmas

J. R. Martín-Solís and R. Sánchez
Universidad Carlos III de Madrid, Avenida de la Universidad 30, 28911-Madrid, Spain

B. Esposito
Associazione Euratom-ENEA sulla Fusione, C.P. 65, 00044-Frascati, Roma, Italy

(Received 30 November 1999; accepted 8 May 2000)

A simple model for a tokamak disruption, taking into account the replacement of the plasma current by the runaway current, is used to evaluate the generation and energy of the runaway population during the current quench phase of a fast disruptive event. The potential efficiency of the ripple resonance and the magnetic fluctuations for runaway current mitigation during plasma disruptions, as well as their dependence on the runaway generation mechanism, are discussed. Predictions are made for the Joint European Torus (JET) [Nucl. Fusion 25, 1011 (1985)] and the projected International Thermonuclear Experimental Reactor (ITER) [ITER EDA Agreement and Protocol 2, International Atomic Energy Agency, Vienna, 1994]. It is shown that the ripple resonance leads to a reduction in the runaway beam energy if the runaway production is dominated by the Dreicer generation process; however, the effect will be negligible if the secondary generation mechanism is included. The effect of anomalous radial runaway losses induced by enhanced magnetic fluctuations is stronger. Large enough levels of magnetic fluctuations, leading to runaway electron loss rates in excess of $10^3 \text{s}^{-1}$, can efficiently limit the number and energy of the runaway electrons. © 2000 American Institute of Physics. [S1070-664X(00)03108-6]

I. INTRODUCTION

The electric fields induced during the current quench phase of a tokamak disruption may give rise to a large number of runaway electrons with energies that are predicted to be as high as several hundreds of MeV. Energetic runaway electrons are often observed in fast discharge terminations due to normal disruptions and the killer pellet injection. Plasma–surface interaction caused by high energy runaway electrons must be minimized in order to avoid a fast decrease in the lifetime of first wall materials. This problem will become more serious for next step devices [such as the proposed International Thermonuclear Experimental Reactor (ITER) (Ref. 3)], where the machine size and plasma current will increase.

Two disruption mitigation methods have been considered to solve the problems related to runaway electrons during a tokamak disruption: 1

(a) The avoidance of runaway electron generation during the disruption current quench. Anomalous radial runaway losses associated with spontaneous and/or externally induced magnetic perturbations have been demonstrated to be effective in realizing this avoidance in the Japan Atomic Energy Research Institute Tokamak-60 Upgrade (JT-60U). 2

(b) The slow termination of the runaway current tail, in which intense plasma–wall interaction is avoided by careful control of the plasma position.

Here we will be primarily interested in the suppression of the runaway electrons and the control of the runaway energy during the current quench phase of fast plasma terminations, in which the time constant of the $I_p$ quench is shorter than the penetration time of the external magnetic fields into the vacuum vessel. This is particularly important in the case of uncontrolled disruptive events in which the first wall materials will be irradiated by energetic runaway electrons created during the disruption current quench.

Runaway generation can be due to either the classical Dreicer process or the secondary generation mechanism. The former is determined by the diffusion in velocity space of electrons with the so-called critical velocity, at which the collisional drag balances the acceleration in the electric field. The latter is due to close Coulomb collisions between runaway electrons and thermal electrons which, as a result, also become runaways. This process has been experimentally demonstrated in the Toroidal Experiment for Technically Oriented Research (TEXTOR) (Ref. 7) and it has been predicted to play an essential role in the formation of the runaway current during disruptions in future tokamak reactors.

On the other hand, the energy that runaways can gain in the electric field is limited by the synchrotron radiation in the curved path of the tokamak, which removes energy at higher rates as the electron energy increases. Additional barriers which might be exploited for the control of the runaway energy can appear due to a resonance between the electron gyromotion and the harmonics of the toroidal field ripple, increasing the energy perpendicular to the magnetic field and therefore the power radiated by the electron, and also due to anomalous radial losses associated with enhanced levels of...
magnetic fluctuations. The parametric dependence of the efficiency of these mechanisms in controlling the energy of a test runaway electron during a disruption has already been analyzed in Refs. 9 and 10. However, in order to make more realistic predictions, the time evolution of the runaway distribution function, as well as the continuous reduction of the toroidal electric field due to the replacement of the plasma current by the runaways must be taken into account.

In this work, we make quantitative estimates of the runaway electron energies and currents attainable during the current quench of a disruption, essentially assuming that the runaways take over the plasma current (as it has been done by Jaspers et al. in Ref. 8 to describe TEXTOR measurements) and including the Dreicer and secondary processes for runaway generation. The model will be presented in Sec. II and applied to the Joint European Torus (JET) (Ref. 11) and ITER. The techniques introduced in Refs. 9 and 10 are used to explore the effect of the ripple resonance and enhanced radial runaway losses on the energy attainable by the runaway electrons and the mitigation of the runaway current. In Sec. III, the question of whether the ripple resonance mechanism may be sufficient to limit the energy of the runaway population will be addressed. The dependence of the efficiency of this scheme on the dominant runaway generation mechanism will be analyzed. Runaway mitigation via enhanced runaway losses (paying particular attention to the effect of the magnetic fluctuations) will be discussed in Sec. IV. The conclusions will be summarized in Sec. V.

II. TOKAMAK DISRUPTION MODEL

A. Runaway current

For an evaluation of the dependence of the runaway current and energy on the plasma parameters during a disruption, it is sufficient to assume that the current carried by the runaway electrons replaces the plasma current $I_p$, therefore reducing the electric field until it vanishes. The model can be described as follows: a disruption occurs in which there is a rapid cooling of the plasma (thermal quench phase). A redistribution of the plasma current takes place, which usually flattens the profile leading to an increase in current (about 15% of the predisruption current) and a short lived negative voltage spike. A current quench follows, in which a large electric field is sustained by the decaying poloidal magnetic field, giving rise to the generation of the runaway population. We assume that during this period the plasma parameters $Z_{\text{eff}}, n_e, T_e$, and therefore the plasma resistivity $\eta$, do not change appreciably, with the electric field given by

$$E_\parallel = \eta (j_p - j_r).$$

$$j_p = j_p, / \pi a^2 k$$

are the average plasma and runaway current densities, respectively ($a$ is the plasma minor radius and $k$ the plasma elongation).

The total current $I_p$ is calculated according to

$$\frac{dI_p}{dt} = \frac{-2 \pi R_0}{L} E_\parallel$$

($R_0$ is the major radius and $L$ the plasma inductance), and the runaway current $I_r$ is obtained taking into account both the classical Dreicer process and the secondary generation mechanism,

$$\frac{dn_r}{dt} = n_e v_0 \gamma (\varepsilon) + \frac{n_e}{\tau_s},$$

where $n_e$ is the runaway density ($j_r = e c n_e$). The first contribution to $dn_r/dt$ in Eq. (3) describes the Dreicer generation; $v_0$ is the collision frequency, $\gamma$ is the runaway birth parameter calculated including relativistic effects, and $\varepsilon = (E_j |E_R|) / (k T_e / m_e c^2)$ ($E_R = N_e e^3 \ln \Lambda / 4 \pi e^2 m_e c^2$). The second term corresponds to the secondary generation mechanism, with $\tau_s$, the characteristic avalanching time, given by

$$\tau_s = \frac{4 \pi e^2 m_e c^3}{e^4 n_e} \sqrt{\frac{3 (5 + Z_{\text{eff}})}{\pi}} \left( \frac{E_j}{E_R} - 1 \right)^{-1}.$$
ligible. This will have a strong effect on the shape of the
creases and, due to the exponential dependence of the
equations, the runaway current production rate and the electric field fo ra5M A
FIG. 2. Simulation of the time evolution of the plasma and runaway cur-
JET disruption. Only Dreicer generation has been considered (εe, = 0.06).

It is observed that, meanwhile in the case of sec-
These three terms describe the synchrotron radiation losses. Their
the first term in Eqs. (5) and (6) is the acceleration due to the
toroidal electric field, and the second term includes the
effect of the collisions with the plasma particles. The third
term describes the synchrotron radiation losses. At each
time step, the toroidal electric field is given by Eq. (1) and, as was indicated above, the plasma parameters are assumed
to remain stationary during the current decay.

The runaway distribution function will be formally given by

\[ f(\gamma, t) = \frac{\int_{0}^{t} \frac{dn_e}{dt}(\gamma, t') \, dt'}{\int_{0}^{\gamma_0} f(\gamma) \, d\gamma}, \]

where \( t = 0 \) denotes the start of the current quench and the integration is carried out over the times \( t' \) for which an electron generated with energy \( \gamma_0 \) would have gained, according to Eqs. (5) and (6), an energy \( \gamma \) at time \( t \).

The accumulated distribution function, the limiting runaway energy \( E_b \) (the maximum runaway energy at the
given time, essentially corresponding to electrons generated at the earliest times during the current quench), the average runaway energy,

\[ E_{av} = \frac{\int_{0}^{\gamma_0} \gamma f(\gamma) \, d\gamma}{\int_{0}^{\gamma_0} f(\gamma) \, d\gamma}, \]

and the total energy in the runaway beam, \( E_b = E_{av} N_r \) [\( N_r = \int_{0}^{\gamma_0} f(\gamma) \, d\gamma \) is the total number of runaway electrons], can be determined.

The distribution function at different times during the
current quench is plotted in Fig. 3(a) for the disruption pre-
ased in Fig. 1. Due to the dominance of the secondary process, the distribution function takes an exponential shape. This result is clearly different from the one illustrated in Fig. 3(b), corresponding to the case shown in Fig. 2, in which it is assumed that the runaway production is dominated by the Dreicer mechanism. As most of the runaway current is formed at the start of the current quench, the distribution function is essentially monoenergetic.

The predictions of the model depend strongly on the
value \( \varepsilon_{e,} \) of \( \varepsilon \) at the start of the current quench. Figures 4(a) and 4(b) show the runaway current versus \( \varepsilon_{e,} \) for a 5 MA JET disruption (\( R_0 = 3 \) m, \( a = 1 \) m, \( Z_{eff} = 3 \), \( T_e = 5 \) eV, \( L = 4 \) \( \mu \)H) and a 24 MA ITER disruption (\( R_0 = 8.14 \) m, \( a = 2.80 \) m, \( Z_{eff} = 3 \), \( T_e = 5 \) eV, \( L = 12 \) \( \mu \)H), respectively. The full lines are obtained including the Dreicer and secondary generation processes; for comparison, the results obtained considering only Dreicer generation (dashed lines) are also shown. The maximum values during the current quench of
the limiting runaway energy $E_{l,max}$, the average energy $E_{av,max}$, and the total energy in the beam $E_{b,max}$ as a function of $\varepsilon_s$ are also given.

As it was already pointed out in Ref. 8, the secondary generation, enhancing the runaway production rate (particularly in the case of ITER), reduces the time during which $E_{ill}$ is high, so that the runaway current is maximized and the runaway energy is reduced. Moreover, since Dreicer generation results in a monoenergetic beam ($E_{av} \approx E_l$) while secondary generation leads to an exponential distribution function at low $\varepsilon_s$ ($E_{av} \ll E_l$), the reduction will be larger at low $\varepsilon_s$ values for the average energy and total energy of the beam than for the limiting runaway energy $E_l$. At high $\varepsilon_s$ values, the Dreicer process always dominates so that the runaway distribution tends to be monoenergetic and $E_{av} \approx E_l$, even when secondary generation is considered.

### III. EFFECT OF RIPPLE RESONANCE

It is well known that a resonance between the electron gyrofrequency and the harmonics of the magnetic field ripple can lead to large synchrotron radiation losses and create an upper bound on the electron energy. A detailed analysis of the dynamics of the runaway-ripple interaction was done in Ref. 10.

The interaction with the $n$th harmonic of the toroidal field ripple takes place at an electron energy $E_n = eB_0R_0c/nN_c$ ($N_c$ is the number of toroidal field coils and $n$ the toroidal harmonic number), and has been implemented in the test particle dynamics following Ref. 10. The efficiency of the resonant interaction is strongly dependent on the ripple amplitude. As it was shown in Ref. 10, for a given electric field and plasma conditions, the ripple amplitude must reach a minimum value $\delta B_{up}/B_0$, calculated following Ref. 10 using the self-consistently calculated electric field during the current quench, is plotted in Figs. 5a and 5b as function of $\varepsilon_s$ for the JET ($N_c = 32$) and ITER ($N_c = 20$) disruption considered in previous figures and toroidal ripple harmonics $n = 1-3$. As before, the dashed lines are obtained assuming only Dreicer generation and the full lines both Dreicer and

---

**FIG. 3.** Time evolution of the runaway distribution function for the simulations shown in Figs. 1 and 2 [(a) Dreicer and secondary generation; (b) only Dreicer generation]. The arrows indicate the direction of the time evolution and $\delta t$ is the time step between successive plots. The first plot in each figure corresponds to the runaway distribution function at time $\delta t$ after the thermal quench.

**FIG. 4.** Predictions of the disruption model for JET (a) and ITER (b): runaway current vs $\varepsilon_s$, maximum limiting and average runaway energies vs $\varepsilon_s$. Full lines, Dreicer and secondary generation; dashed lines, only Dreicer generation.
secondary generation. The results presented in the figures can be summarized as follows:

(a) The stronger runaway-ripple interaction (lower $\delta B_{up}$ required) takes place at the lower harmonics. Thus, the most important ripple effects are expected for $n=1$ in JET ($E_n\approx84\text{ MeV}$) and $n=2$ in ITER ($E_n\approx350\text{ MeV}$). For $n=1$ in ITER, the resonant energy is too large ($\approx700\text{ MeV}$) to have a remarkable effect on the runaway energy.

(b) $\delta B_{up}$ decreases with increasing $e_s$ as the runaway production is then larger and therefore the electric field lower, the electrons being more easily stopped at the resonance.

(c) For a given value of $e_s$, secondary generation improves the ripple efficiency with respect to the Dreicer case, lowering the ripple amplitude $\delta B_{up}$ required to block the runaway energy, as the electric field is lower due to the larger runaway production.

(d) Nevertheless, for secondary generation, in comparison with the case without ripple, the ripple resonance will play a role only at low $e_s$ values, when the energy $E_{l,max}$ without ripple is larger than the resonant energy $E_n$. Even then, due to the exponential nature of the runaway distribution function at low $e_s$, only a small fraction of the runaway population (at the highest energies) will be affected and the total energy in the runaway beam will not be substantially changed. If only Dreicer generation is assumed, the effects are larger due to the higher $E_{l,max}$ values (without ripple) and, as the runaway beam is monoenergetic in this case ($E_{av}=E_l$), $E_b$ can noticeably change. This is illustrated in Fig. 5 in which the total energy $E_{b,max}$ in the runaway beam with and without considering ripple effects is plotted vs $e_s$ for the 5 MA JET ($n=1$) disruption and the 24 MA ITER ($n=2$) disruption previously considered. When secondary generation is included, the effect of the ripple resonance on $E_b$ is negligible. For these calculations, a simple evaluation of the magnetic field ripple in JET and ITER, obtained by modeling the coils by infinite straight-line conductors,\cite{10,17} has been used.

![FIG. 5. Top [(a) and (b)]: Minimum (normalized) ripple amplitude $\delta B_{up}/B_0$ for efficient runaway-ripple interaction vs $e_s$ ($n=1-3$); Bottom [(a) and (b)]: Maximum energy in the runaway beam vs $e_s$ [full line, Dreicer and secondary generation; dashed line, Dreicer generation; dotted line, Dreicer generation and interaction with the $n=1$ (JET) and $n=2$ (ITER) ripple harmonics]. When secondary generation is included, the results for the runaway beam energy are the same with and without ripple.](image)

**IV. RADIAL RUNAWAY LOSSES**

Loss mechanisms that can deplete the population of runaways, such as turbulent diffusion processes, can be used as an effective tool for the suppression of runaway electrons during a disruption and the control of the maximum energy that the runaways can reach.\cite{18} In fact, disruption mitigation methods based on spontaneously or externally induced macro-scale magnetic perturbations, giving rise to anomalous radial runaway losses, are being actively investigated.\cite{2}

The effect of the radial runaway losses on disruption generated runaway electrons will be accounted for in the model presented in Sec. II by including the loss term $-n_r/\tau_{dr}$ in Eq. (3) for the runaway production rate and the friction force $-q/\tau_{dr}$ in Eqs. (5) and (6) for the energy dynamics,\cite{9} where $\tau_{dr}=a^2/\rho D_r$ is the characteristic diffusion time associated with the runaway losses (phenomenologically described by the radial diffusion coefficient $D_r$), $\tau_{dr}=\nu\tau_d$ is the normalized diffusion time, and $j_0$ is the first zero of the Bessel function $J_0$.

In Fig. 6, a comparison is presented between the time evolution of $I_p$, $I_r$, and $E_b$ during the current decay of the disruption illustrated in Fig. 1 for zero radial diffusion (full line) and for a runaway loss rate $\tau_d^{-1}=170\text{ s}^{-1}$ (dashed line). Note that, when the effect of the runaway losses is taken into account, the runaway current $I_r$ goes through a maximum, decaying to zero later on. It is also of interest that, because of the lower percentage of runaway current, the electric field
becomes larger than for the case in which no runaway losses are considered ($\tau_d^{-1} = 0$).

Application of the model to the experiments described in Ref. 2 is shown in Fig. 7. The experiments were performed in the JT-60U tokamak, in ohmically heated discharges terminated by the killer pellet injection (KPI). The plasma current at the start of the current quench was $\sim 2$ MA, the toroidal magnetic field at the center of the vacuum vessel $B_0 \sim 2.5$ T, the safety factor at 95% of total flux $q_{95} = 3.35 - 4$, and the line averaged density $\bar{n}_e = (0.6 - 0.8) \times 10^{19}$ m$^{-3}$. Radial runaway losses associated with enhanced magnetic fluctuations induced by an external helical field resulted in the suppression of runaway electrons in fast discharge terminations with a maximum speed of the current quench $dI_p/dt = -90$ to $-130$ MA/s, usually fast enough to produce a runaway tail during a normal disruption. In Fig. 7, the predicted maximum value $I_{r,\text{max}}$ of the runaway current, the maximum limiting and average runaway energies, and the maximum value of the energy in the runaway beam during the disruption current quench are plotted vs the runaway loss rate $\tau_d^{-1}$ for $\epsilon_s = 0.05$, corresponding to typical plasma parameters during fast plasma terminations in JT-60U and $dI_p/dt = -100$ MA/s. The results indicate that proper control of the number and energy of the runaway population is reached for $\tau_d^{-1} > 10^3$ s$^{-1}$ ($D_r > 340$ m/s$^2$). It is also interesting to note in Fig. 7 the existence of a range of $\tau_d^{-1}$ values $[1 < \tau_d^{-1} < 500]$ for which the limiting runaway energy $E_{l,\text{max}}$ becomes larger than in absence of diffusion losses. This is due to the acceleration by the increased electric field associated with the lower percentage of runaway current, as it was explained in the paragraph above.

The interpretation in terms of the level of the magnetic fluctuations is more complicated because it requires a proper model to describe the radial diffusion induced by the macroscale magnetic perturbations during a major disruption. The behavior of runaway electrons in strong magnetohydrodynamic (MHD) turbulence consisting of magnetic islands...
with the widths expected during a disruption has been simulated numerically in Ref. 19 leading to the following conclusions.4

(a) Due to the toroidal asymmetry of the magnetic perturbations, the conservation of the toroidal runaway momentum is broken. This breakdown is called “scattering” and gives rise to the collisionless loss of the runaway electrons.

(b) Radial diffusion of electrons is enhanced by overlapping of magnetic islands.20 Assuming free streaming along the field lines, an estimate for the collisionless loss in the fully stochastic magnetic field can be obtained using the diffusion coefficient,20

$$D_r = D_m v_{||},$$

where $v_{||}$ is the parallel electron velocity and $D_m$ is the magnetic line diffusion coefficient.

This description is valid under the assumption that the magnetic field is static and stochastic everywhere,21 and that the characteristic radial width of the turbulence is larger than the drift of the runaway orbit, which should be the case for the macroscale magnetic perturbations during a disruption, so that no enhancement of the runaway confinement will take place due to phase averaging.22 The magnetic line diffusion coefficient $D_m$ will depend on the characteristics of the magnetic fluctuations. A sensible approach, given by $D_m = L_{||} b^2$ ($b$ is the normalized radial magnetic fluctuation amplitude $b = B_r / B_0$, $L_{||} = \pi q_0 R_0$ is the parallel correlation length of the magnetic fluctuations, and $q_0$ the safety factor), should be valid for MHD turbulence consisting of “ macroscale” magnetic islands (as $L_{||} b < \delta$, with $\delta$ the characteristic radial scale length of the fluctuations). Using this estimate, the condition $D_r > 340 \text{ m/s}^2$ for runaway avoidance derived from Fig. 7, would lead to $b > 2 \times 10^{-4}$, in rough agreement with the measurements of the radial magnetic fluctuations in the JT-60U experiments [$b \sim (2-8) \times 10^{-4}$].2

(c) Even when the overlapping of magnetic islands disappears, accumulation of the scattering by macroscale islands of several centimeters width causes the collisionless loss of relativistic runaway electrons.19 The resultant runaway loss rate becomes $10^3-10^4 \text{ s}^{-1}$, sufficiently high to avoid and suppress runaway generation.19

Figure 8 shows, as function of $\epsilon_s$ and for different values of the runaway loss rate $\tau_d^{-1}$, the predicted maximum runaway current $I_{r,max}$, and runaway energy ($E_{i,max}$, $E_{av,max}$, and $E_{b,max}$) during the current quench phase of a 24 MA ITER disruption. Its dependence on $\tau_d^{-1}$ for different $\epsilon_s$ values is illustrated in Fig. 9. Two main conclusions can be drawn from these figures.

(1) Avoidance of runaway electron generation and control of the runaway energy to a low level during the current quench of a fast disruptive event in ITER will be reached for $\tau_d^{-1} > 10^3 \text{ s}^{-1}$ ($D_r > 2400 \text{ m/s}^2$).

(2) Nevertheless, at intermediate loss rate levels $10 < \tau_d^{-1} (\text{s}^{-1}) < 500$ and for $\epsilon_s > 0.05$ (see Fig. 8), the runaway energy may become larger than for zero runaway losses, even when the runaway current has been reduced. The reason is that, because of the decrease of the runaway current, the electric field during the current decay is higher (as illustrated in Fig. 6). Thus, if the electrons do not escape from the plasma at a fast enough rate, the energy gained in the increased electric field can be large.

Calculations made for the 5 MA JET disruption show a qualitative behavior similar to that found in Figs. 8 and 9 for the ITER case.
V. CONCLUSIONS

A simple model for a tokamak disruption and runaway generation, assuming that the runaway current is replacing the plasma current, together with a test particle description of the runaway energy dynamics, has been used to estimate the runaway current and energy during the disruption current quench. Predictions have been made for the Joint European Torus (JET) and the planned ITER project.

The maximum runaway current $I_r$, limiting electron energy $E_{l,\text{max}}$, average electron energy $E_{\text{av},\text{max}}$, and total energy $E_{b,\text{max}}$ in the runaway beam vs $\tau_d^{-1}$, calculated taking into account the Dreicer and secondary generation mechanisms for the ITER disruption considered in previous figures and for different $\varepsilon_s$ values.

![Graph](image.png)

FIG. 9. Maximum runaway current $I_{r,\text{max}}$, limiting electron energy $E_{l,\text{max}}$, average electron energy $E_{\text{av},\text{max}}$, and total energy $E_{b,\text{max}}$ in the runaway beam vs $\tau_d^{-1}$, calculated taking into account the Dreicer and secondary generation mechanisms for the ITER disruption considered in previous figures and for different $\varepsilon_s$ values.

V. CONCLUSIONS

A simple model for a tokamak disruption and runaway generation, assuming that the runaway current is replacing the plasma current, together with a test particle description of the runaway energy dynamics, has been used to estimate the runaway current and energy during the disruption current quench. Predictions have been made for the Joint European Torus (JET) and the planned ITER project.

The runaway current, the maximum energy that an individual electron can reach, the average runaway energy and the total energy in the runaway beam have been calculated as function of the parameter $\varepsilon_s E_{||}/n_e T_e$ at the start of the current quench, which characterizes the plasma conditions and the runaway production during the disruption. As it was already shown in Ref. 8, larger production rates (runaway current) lead to lower energies as the electric field during the disruption is decreased. The effect is particularly important when the runaway production is dominated by the secondary generation process, not only because the runaway current is larger, but also because, due to the exponential nature of the distribution function, the reduction (with respect to the case when only Dreicer generation is included) in the average energy of the runaway population and in the runaway beam energy will be even larger than for the limiting runaway energy $E_l$.

The role played by the ripple resonance mechanism on the control of the runaway energy during a disruption has also been analyzed. The results indicate that remarkable ripple effects are not expected for typical JET and ITER conditions during disruptions, unless secondary generation is avoided. For large production rates, the runaway energy without ripple is less than the resonant energy, while for low runaway production, because the runaway distribution function will be exponential, only a small population (at the highest energies) is affected, and the average and beam runaway energies will remain essentially unchanged.

Finally, the efficiency of a runaway mitigation scheme based on enhanced radial runaway losses has been investigated. Application of the model has shown that runaway loss rates larger than $10^{3} \text{s}^{-1}$ must be enough to avoid and suppress the generation of runaway electrons during the current quench phase of JT-60U disruptions. The corresponding level of magnetic fluctuations required for runaway mitigation will be determined by the mechanism dominating the runaway loss. Hence, if overlapping of magnetic islands is taking place during the current quench, a sensible estimate of the runaway diffusion coefficient assuming free streaming along the magnetic field lines, based on Eq. (9), would lead to a fluctuation level $\delta > 2 \times 10^{-4}$ for runaway suppression, in agreement with the experimentally determined radial magnetic perturbations. Nevertheless, even in absence of island overlapping, the loss of electron confinement due to the breakdown of toroidal momentum conservation leads to the required loss rate ($\sim 10^3 - 10^4 \text{s}^{-1}$) for runaway avoidance during fast plasma shutdown JT-60U experiments.

It has been found that loss rates larger than $10^3 \text{s}^{-1}$ $(D_r > 2400 \text{m/s}^2)$ should be also enough for runaway electron generation suppression and control of the runaway energy during the current quench phase of fast discharge terminations in ITER. In the case of island overlapping, using Eq. (9) to estimate $D_r$, this would lead to a fluctuation level $\delta > 4 \times 10^{-4}$ for runaway avoidance. However, at intermediate loss rate levels ($\sim 10^3 - 500 \text{s}^{-1}$) and for $\varepsilon_s > 0.05$, the energy in the runaway beam may become larger than for zero loss rate. Some care must be taken in this situation to keep control of the plasma position during the disruption current quench as, otherwise, the interaction with the first wall materials might yield more damage than in the absence of fluctuations.
ACKNOWLEDGMENT

This work was done under financial support from Dirección General de Enseñanza Superior (DGES) Project No. PB96-0112-C02-01.