Magnetic stochasticity and runaway electron dynamics in vertically unstable plasmas during tokamak disruptions

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1. Introduction. In large devices like ITER, the strong amplification of an initial runaway seed due to the avalanche mechanism [1] during tokamak disruptions can lead to runaway electron (RE) currents of several MAs, posing serious threats to the system integrity. The vertical instability of the runaway beam can cause wall contact, leading to large power loads on the plasma-facing components (PFCs) and material damage [2], requiring proper mitigation strategies.

Magnetic stochasticity during the thermal quench (TQ) and current quench (CQ) phases of the disruption, leading to RE losses, can have a strong effect on the final RE current and energy deposited on the PFCs [3].

This work investigates whether magnetic stochasticity during the CQ phase of the disruption in vertically unstable plasmas can cause sufficient RE losses to prevent a significant RE avalanche and energy deposition when the plasma contacts the wall.

2. The Model. The analysis uses a 0-D model [4] which approximates the plasma-wall system by three parallel circular rings of radius R_0, described by the circuit equations:

$$L_w\frac{dI_1}{dt}+L_{12}\frac{dI_2}{dt}+L_{wp}\frac{d}{dt}\left[1-\kappa\ln(1+\xi)\right]I_p=-R_wI_1, \qquad (1)$$

$$L_{12}\frac{dI_1}{dt}+L_w\frac{dI_2}{dt}+L_{wp}\frac{d}{dt}\left[1-\kappa\ln(1-\xi)\right]I_p=-R_wI_2, \qquad (2)$$

$$L_{wp}\frac{d}{dt}\left[1-\kappa\ln(1+\xi)\right](I_1+I_e)+L_{wp}\frac{d}{dt}\left[1-\kappa\ln(1-\xi)\right](I_2+I_e)+\frac{d}{dt}(L_pI_p)= \qquad (3)$$
$$=-R_p(I_p-I_r),$$

where I_1, I_2 are the currents of the bottom and top conductors, respectively, and represent the current in the wall, and the current in the middle conductor is the plasma current, I_p, which can move vertically. A static external magnetic field created by two constant circular currents, I_e, is also included [4]; I_r and I_{OH} are the RE and ohmic currents respectively ($I_p = I_r + I_{OH}$), $\xi \equiv z/a_w$ is the normalized vertical displacement of the plasma, $\kappa = (\ln[8R_0/a_w]-2)^{-1}$, R_w and L_w are the resistance and inductance of the wall conductors, respectively, L_{12} the mutual inductance between the wall conductors, and $L_{1p} = L_{wp}[1-\kappa\ln(1+\xi)]$, $L_{2p} = L_{wp}[1-\kappa\ln(1-\xi)]$, the mutual inductances between the plasma and the wall conductors, respectively; L_p is the total plasma inductance, $L_p \equiv L_{int} + L_{ext}$, where L_{int} and L_{ext} are the internal and external plasma inductances, respectively, with $L_{ext} \equiv \mu_0R_0(\ln[8R_0/a]-2)$, and R_p is the plasma resistance, $R_p \approx \eta\, 2R_0/a^2$ (η is the plasma resistivity and a the plasma minor radius). The force free-constraint will be used for the vertical plasma motion [4], $\xi = (I_1-I_2)/(I_1+I_2+2\,I_e)$, and the generation and loss of the RE current is described by:

$$\frac{dI_r}{dt}=\left(\frac{ec\left(E_\parallel-E_R\right)}{T_r}-\frac{1}{\tau_d}+\frac{2\dot{a}}{a}\right)I_r. \qquad (4)$$

The first term approximates the RE avalanche generation, with $T_r \approx m_ec^2\ln\Lambda\, a_Z$ and $a_Z \approx \sqrt{3\,(5+Z)\,/\pi}$, $E_R = n_ee^3\ln\Lambda/4\pi\varepsilon_0^2m_ec^2$ is the critical field for RE generation, and the parallel electric field is determined by the resistive current in the plasma, $E_\parallel = \eta\,(j_p - j_r)$, with $j_{p,r} = I_{p,r}/\pi a^2 k$, and k the plasma elongation. The second term corresponds to the deconfinement of the RE current during the magnetic stochastic phase, described by a characteristic loss time, τ_d [5], and the third term represents the loss of REs during scraping-off once the plasma touches the wall [6].

For simplicity, we assume *ad-hoc* constant values for $\ln\Lambda$ and Z. In fully ionized plasmas, Z is the effective ion charge, whereas during disruptions, with impurities, Z includes the effect of the scattering of the REs on the impurity ions, and the expression for the avalanche generation must include the effect of the collisions with the bound electrons.

3. Runaway deconfinement and energy deposition. It is assumed that the stochastic phase starts after the TQ of the disruption and is operative for a time interval τ during the CQ, after which the reformation of the magnetic flux surfaces occurs ($\tau_d \to \infty$).

Figure 1 shows an example of a 15 MA ITER-like pre-disruption plasma current ($\tau_w = 0.5$ s, $T_e = 5$ eV, $n_e = 10^{22}$ m^{-3}) for which magnetic stochasticity with characteristic loss time $\tau_d = 2$ ms extends during the CQ phase of the disruption for a period of $\tau = 5$ ms. The initial RE seed is assumed $I_{\rm seed} = 30$ kA. The plasma and RE currents are shown in Fig. 1(a) (black lines). As a reference, the results assuming no runaway deconfinement ($\tau_d \to \infty$; red lines) are also shown. The RE current (dashed line) at the time the plasma contacts the wall (see vertical line) is ~ 0.7 MA, much smaller due to the effect of the RE losses than in the case $\tau_d \to \infty$ (no RE losses) when the RE current at the time the beam touches the wall is ~ 7 MA. Nevertheless, the reduction in the RE current leads to a larger plasma vertical velocity and, hence, to an increase of the electric field during scraping-off as illustrated in Fig. 1(b), leading to a substantial energy deposition on the REs, as shown in Fig. 1(c). This energy is calculated as:

$$\Delta W_{\rm run} \approx 2\pi R_0 \int_0^t I_r\left(E_\parallel - E_R\right) dt'. \qquad (5)$$

Note that, when the surface $q_a = q(r=a) = 2$ is reached, $\Delta W_{\rm run}^{q=2} \sim 35$ MJ, and the total amount of energy deposited during scraping-off is $\Delta W_{\rm run} \sim 120$ MJ. Finally, Fig. 1(d) presents the time evolution of the normalized vertical plasma displacement, ξ.

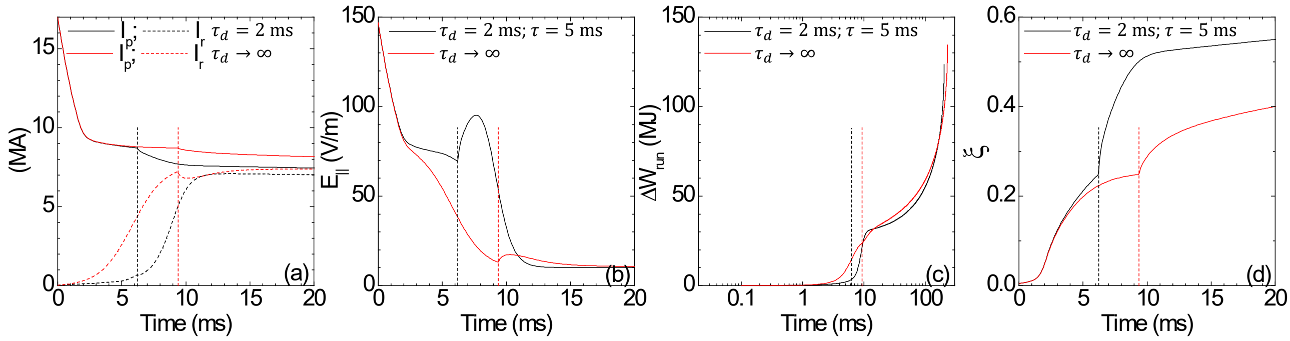

Figure 1: For a 15 MA ITER-like pre-disruption plasma current, assuming $I_{\rm seed} = 30$ kA, $T_e = 5$ eV, $n_e = 10^{22}$ m^{-3}, and RE losses with characteristic deconfinement time $\tau_d = 2$ ms for $\tau = 5$ ms during the CQ (black lines): Time evolution of (a) plasma and RE currents, (b) electric field, (c) energy deposited on the RE beam and (d) normalized vertical plasma displacement. The vertical line indicates the time the plasma contacts the wall. The red lines show the results assuming no deconfinement ($\tau_d \to \infty$).

Hence, it is of interest to analyze the conditions under which the loss of REs during the CQ phase of the disruption can result in a potentially less worrying scenario from the point of view of the energy transferred to the REs, taking into account the effects associated to the scraping-off of the RE beam.

Figure 2(a) depicts, for the same disruption conditions than Fig. 1, the RE current when the plasma touches the wall, I_r^c, vs. τ/τ_d for three levels of stochasticity, $\tau_d = 0.5$, 1 and 2 ms, respectively. It is observed that I_r^c decays exponentially with τ/τ_d, $I_r^c \sim \exp(-\tau/\tau_d)$, if the stochastic phase ends before the plasma touches the wall ($\tau < t_c$, where t_c is the time to reach the wall). If $\tau > t_c$ the RE current at contact saturates, $I_r^c = I_r(t = t_c)$, corresponding to the horizontal lines shown in the figure. The lower τ_d is, the larger will be the minimum value of τ/τ_d ($\equiv t_c/\tau_d$) required to reach the saturation which, therefore, will occur at lower values of I_r^c. Hence, for $\tau_d = 2$ ms, I_r^c saturates at ~ 0.4 MA, and at ~ 20 kA for $\tau_d = 1$ ms, whereas for $\tau_d = 0.5$ ms saturates at ~ 50 A.

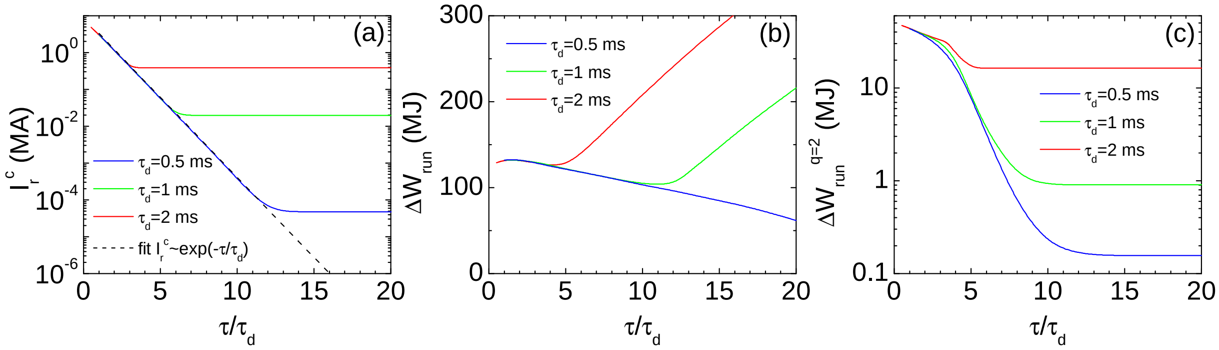

Figure 2: For the same conditions than Fig. 1, (a) RE current at the time the plasma hits the wall vs. τ/τ_d. (b) Energy transferred to the REs during scraping-off vs. τ/τ_d. (c) Energy deposited on the runaway electrons during scraping-off when $q_a = 2$ is reached vs. τ/τ_d.

Figure 2(b) shows the energy transferred to the runaways during scraping-off vs. τ/τ_d. When the stochasticity period extends to the scraping-off phase ($\tau > t_c$), $\Delta W_{\rm run}$ shows an increase mainly because the lower RE current due to the losses results in a faster vertical displacement and, hence, in a larger associated electric field, which increases the RE avalanche, unless the losses are sufficiently strong (as for the case $\tau_d = 0.5$ ms). However, it must be taken into account that the deposition of energy onto the RE electrons should not take place during the whole scraping-off phase as, due to decrease of the plasma radius, the limit $q_a = 2$ is reached, and a deconfinement of the runaway beam must occur following $q_a = 2$. Hence, Fig. 2(c) shows the amount of energy deposited on the REs by the time $q_a = 2$ is reached, $\Delta W_{\rm run}^{q=2}$, which can be noticeably lower than the values estimated for the full scraping-off of the beam (Fig. 2(b)). According to these results, $\Delta W_{\rm run}^{q=2}$ decreases with τ/τ_d until, once the stochasticity time interval (τ) is larger than the time to contact the wall (t_c), it saturates to a constant value which decreases for low τ_d (from ~ 15 MJ for $\tau_d = 2$ ms, to ~ 0.1 MJ for $\tau_d = 0.5$ ms). Moreover, as discussed in [6], for low enough τ_d (< 0.1 ms) following $q_a = 2$, negligible additional energy deposition on the REs should be expected.

An estimate of the energy deposited by the REs on the PFCs, $W_{\rm PFC}$, can be obtained as $W_{\rm PFC} \equiv \Delta W_{\rm run} - W_{\rm kin}$ ($W_{\rm kin}$ is the instantaneous kinetic energy of the RE beam [5]), and the power deposited by the REs on the PFCs, $P_r(t) \equiv {\rm d}W_{\rm PFC}/{\rm d}t$. This evaluation of the REs loads on the PFCs can be used to get simple estimates of the resulting increase of the surface temperature of the first wall materials using the one-dimensional solution of the heat diffusion equation in a semi-infinite solid, including the effect of the penetration depth of the REs in the material, which assuming an exponential decay of the RE energy deposition into the PFCs yields [6]:

$$\Delta T = \frac{\kappa}{K\delta} \int_0^t q_r(t')\, e^{\kappa\,(t-t')/\delta^2}\, {\rm erfc}\left(\frac{\sqrt{\kappa\,(t-t')}}{\delta}\right) dt', \qquad (7)$$

($\kappa = K/\rho c$, where K is the solid heat conductivity, c the heat capacity, and ρ the mass density, δ is the e-folding length of the heat source due to the REs into the PFCs, $\mathrm{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-x'^2}\, dx'$ the complementary error function, and $q_r \equiv P_r/A_w$ is the RE heat flux density, where A_w is the RE wetted area). Using these estimates of the power loads due to the REs and ΔT in the material, the minimum wetted area, $A_{\min}$, to avoid melting has been evaluated for the case of REs of a few MeVs in Be ($\Delta T < 1000$ K, $\delta = 2$ mm) and W ($\Delta T < 3200$ K, $\delta = 0.09$ mm) for the ITER-like disruption of Fig. 1 (see Fig. 3(a)). By the time the surface $q_a = 2$ is reached, $A_{\min}$ can be as large as ~ 1 m^2 for both materials. Figures

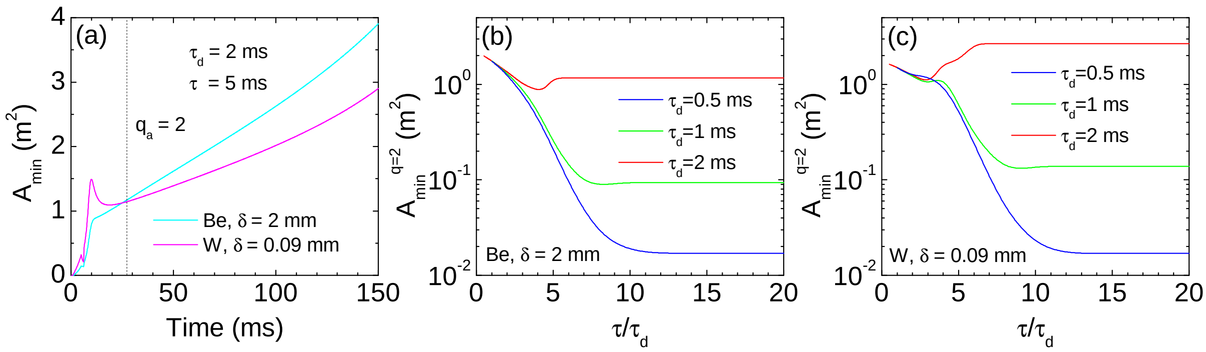

Figure 3: For similar conditions than previous figures: (a) $A_{\min}$ for Be and W melting vs. time for $\tau_d = 2$ ms and $\tau = 5$ ms; (b) $A_{\min}^{q=2}$ vs. τ/τ_d for Be; (c) $A_{\min}^{q=2}$ vs. τ/τ_d for W.

3(b), (c) show under these conditions the dependence of $A_{\min}$ at $q_a = 2$ ($A_{\min}^{q=2}$) on τ/τ_d for Be and W, respectively. Again, $A_{\min}^{q=2}$ is found to decrease with τ/τ_d, saturating when the plasma contacts the wall at a value which decreases for increasing stochasticity (i.e., lower τ_d). The saturation values do not differ much for Be and W, ranging from ~ 1 m^2 for $\tau_d = 2$ ms, to ~ 0.1 m^2 for $\tau_d = 1$ ms, and ~ 0.01 m^2 for $\tau_d = 0.5$ ms.

4. Conclusions. The impact of magnetic stochasticity during the CQ phase of vertically unstable disruption generated RE beams has been analyzed. Strong enough losses (low τ_d) and a sufficiently long stochastic phase (τ) are required to control the damage onto the PFCs. I_r^c, $\Delta W_{\mathrm{run}}^{q=2}$ and $A_{\min}^{q=2}$ are found to decrease when τ/τ_d increases unless the beam contacts the wall, leading to saturation for $\tau > t_c$. It is obtained that, for low temperatures of the residual ohmic plasma during the disruption ($\sim$ eVs), in order to reduce $A_{\min}$ to values below ~ 0.1 m^2, $\tau_d < 1$ ms and $\tau/\tau_d > 5$ would be needed, and I_r^c should be kept quite low, $\sim$ few to tens of kAs.

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References

[1] H. H. Jayakumar et al., Phys. Lett. A **172**, 447 (1993).
[2] E. Hollmann et al., Phys. Plasmas **22**, 056108 (2015).
[3] K. Särkimäki et al., Nucl. Fusion **62**, 086033 (2022).
[4] D. I. Kiramov and B. N. Breizman, Phys. Plasmas **24**, 100702 (2017).
[5] J. R. Martín-Solís, Phys. Plasmas **28**, 032505 (2021).
[6] J. R. Martín-Solís et al., Nucl. Fusion **62**, 076013 (2022).