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RUNAWAY ELECTRON AVALANCHE AND ENERGY DEPOSITION DURING SCRAPING-OFF OF VERTICALLY UNSTABLE DISRUPTION GENERATED RUNAWAY BEAMS

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Abstract

In ITER, a disruption-induced runaway electron (RE) current is expected to be vertically unstable, leading to the scraping-off of the RE beam when the plasma touches the wall. Here, the effect of the scraping-off of vertically unstable plasmas during fast deconfinement of disruption generated REs is investigated using a 0D three loop model for the plasma current and the currents in the wall [1,2]. It is found that the drop of the RE current during deconfinement leads to the vertical acceleration of the plasma and to a large increase of the electric field when it hits the wall during scraping-off, yielding a substantial RE avalanche which can result in the recovery of the RE current and a noticeable increase in the amount of energy transferred to the RE population. The energy deposited on the runaways, ΔW_{run}, increases with the characteristic RE deconfinement time, τ_d, and a reduction of ΔW_{run} to low enough values in ITER (~ few MJs) requires a short enough τ_d, below 0.5 ms for low T_e (~few eVs) and, in that case, recovery of RE current does not occur. Also, ΔW_{run} decreases when the resistive decay time of the residual ohmic plasma, τ_{res}, increases, due to the larger induced ohmic current, so that, overall, the energy transferred to the REs increases with τ_d/τ_{res}. The conversion of magnetic energy into RE energy is larger when the deconfinement starts closer to the wall or during the scraping-off phase, but the effect is not strong unless it takes place well inside the scraping-off. The 0D three loop model has also been used to analyze the effect of magnetic stochasticity during the disruption current quench (CQ) of vertically unstable RE beams, aiming to the investigation of the conditions to avoid a large RE energy deposition on the plasma facing components (PFCs) during scraping-off of the plasma. Strong enough losses (low characteristic RE loss time, τ_d) during the stochastic phase and a sufficiently long stochastic period (τ) before the reformation of the flux surfaces are found to be needed to control the PFC damage. For given values of (τ,τ_d), the RE current at the time the plasma contacts the wall (I_r^c) and the energy transferred to the REs during scraping-off decrease when τ/τ_d increases, unless the plasma hits the wall during the stochastic period (contact time $t_c < \tau$), leading to saturation for $\tau > t_c$. Thus, it is obtained that, for low temperatures (~ few eVs) of the residual ohmic plasma during the disruption in ITER, $\tau_d < 1$ ms and $\tau/\tau_d > 5$ would be required to reduce ΔW_{run} to a few MJs or below. Moreover, independently of the model used for the magnetic stochasticity and the RE losses, it is found that the relevant parameter determining the energy deposited on the REs during scraping-off is the RE current at the time the plasma hits the wall, I_r^c, and this study suggests that I_r^c should be kept quite low, in a range ~few kAs to tens of kAs.

1. INTRODUCTION

Large MA RE currents can be generated during the CQ phase of tokamak disruptions, mainly due to the avalanche mechanism, which, in case of interacting with the first wall structures, could yield serious damage, demanding for the development of efficient mitigation schemes for the disruption generated REs. The benign termination of RE beams by injection of low-Z impurities [3,4] leading to the deconfinement of the REs without conversion of magnetic into RE kinetic energy, is being actually considered as a promising RE mitigation scheme. In this work, the effect of the vertical plasma motion and the scraping-off of a vertically unstable disruption generated RE beam when it touches the wall on the deconfinement of the RE current is investigated, focusing on the amount of energy that can be deposited on the REs. With that aim, a 0D three-loop model [1] including the vertical plasma motion together with the generation of REs and the loss of the RE current during deconfinement is used. Due to the decay of the RE current during deconfinement, the beam is vertically accelerated, leading to the increase of the electric field when it touches the wall, which can yield a large RE avalanche, regeneration of the RE current and a substantial amount of energy deposited on the REs. The dependence of the energy transferred to the REs during deconfinement on the characteristic RE loss time, τ_d, the resistive time of the residual ohmic plasma during the disruption CQ, τ_{res}, and the initial RE current and position of the RE beam is discussed (Sec.2).

On the other hand, a common feature of disruptions is magnetic stochasticity. It has been suggested that stochastic magnetic fields, both during the termal quench (TQ) and the CQ phases of the disruption, leading to RE losses, can have an important effect on the final RE current and, so, on the potential RE damage on the PFCs [5]. Here, in Sec.3, the effect of magnetic stochasticity during the disruption CQ of vertically unstable RE beams is analyzed using the 0D three loop model, aiming to the investigation of the conditions required to avoid a large RE energy deposition on the PFCs during the scraping-off of the beam. The conclusions are summarized in sec.4.

Finally, note that, along this paper, we will use the term deconfinement for the transport or stochastic losses, in contrast to the scraping-off losses when the plasma contacts the wall.

2. FAST DECONFINEMENT OF DISRUPTION GENERATED REs

2.1. The model

A 0D model is used [1], which approximates the plasma- wall system by three parallel thin circular coaxial rings of radius R_0. The bottom and top conductors, with currents I_1, I_2, respectively, represent the current in the wall, while the middle conductor corresponds to the plasma current, I_p, which can move vertically. A external static magnetic field created by two constant circular currents, I_e, is also included. The circuit equations are:

$$L_w \frac{dI_1}{dt} + L_{12}\frac{dI_2}{dt} + L_{wp}\frac{d}{dt}[1-\kappa\, ln(1+\xi)]\, I_p = -R_w I_1, \tag{1}$$

$$L_{12} \frac{dI_1}{dt} + L_w\frac{dI_2}{dt} + L_{wp}\frac{d}{dt}[1-\kappa\, ln(1-\xi)]\, I_p = -R_w I_2, \tag{2}$$

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

where 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 plasma displacement (a_w is the distance between the two wall conductors), $\kappa = (ln[8R_0/a_w] - 2)^{-1}$, R_w, L_w are the resistance and inductance of the wall conductors, respectively, L_{12} the mutual inductance between the wall conductors, $L_{1p} = L_{wp}[1-\kappa\, ln(1+\xi)]$, $L_{2p} = L_{wp}[1-\kappa\, ln(1-\xi)]$, the mutual inductances between the plasma and the wall conductors, respectively; $L_p = L_{int} + L_{ext}$ (L_{int} and L_{ext} are the internal and external plasma inductances, respectively), and R_p is the plasma resistance. The force free constraint, $\xi = (I_1 - I_2)/(I_1 + I_2 + 2I_e)$ is used for the vertical plasma motion [1].

The time evolution of the RE current is calculated using

$$\frac{dI_r}{dt} \approx \frac{ec(E_{||} - E_R)}{T_r} I_r - \frac{I_r}{\tau_d} + \frac{2\dot{a}}{a} I_r\,. \tag{4}$$

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

For simplicity, *ad-hoc* constant values for $ln\Lambda$ and Z are assumed. In fully ionized plasmas, Z is the effective ion charge. During disruptions with impurities, Z includes the effect of the scattering of the REs on the impurity ions. Also, in that case, the expression for the avalanche amplification must be generalized to include the effect of the collisions with the bound electrons.

2.2. Fast RE deconfinement and energy conversion

An example of deconfinement of a vertically unstable disruption generated RE current during an ITER-like disruption ($\tau_w \equiv L_w/R_w = 0.5\ s$), with $T_e = 5\,eV$ and $n_e = 10^{22}m^{-3}$, is shown in Fig.1. The start of deconfinement (*t = 0*) occurs at the vertical position $\xi_0 = 0.22$ (before the plasma contacts the wall). The initial RE current is I_r^0= 4 MA, the plasma current $I_p^0 \sim$ 9 MA, and $\tau_d = 1\ ms$. The left figure shows the time evolution of the numerically calculated plasma and RE currents (black lines) obtained solving Eqs. (1) – (4) and using the force free condition for the vertical motion. The evolution of I_p and I_r assuming no RE deconfinement ($\tau_d \to \infty$; red lines) is also plotted in the figure. Due to the deconfinement, the RE current decays leading to the acceleration of the plasma (as the plasma velocity increases for lower RE currents [2]), and the beam contacts the wall before the case without deconfinement (indicated by the vertical lines in the figure). Once the plasma contacts the wall, the scraping-off phase starts during which, as a result of the larger plasma velocity, the electric field increases in comparison with the case without RE deconfinement. The increase in the electric field yields a larger RE avalanche which can lead to the regeneration (recovery) of the RE current (left Fig.1) until the final termination phase of the scraping-off.

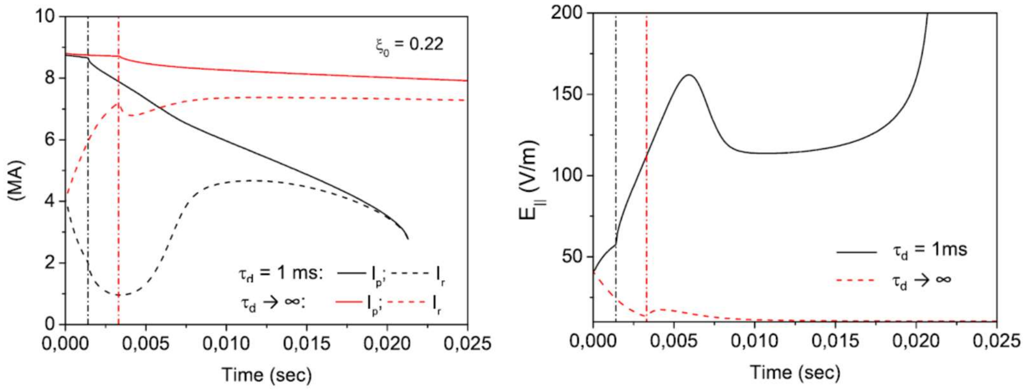

FIG.1 Fast deconfinement of a RE current generated during an ITER-like disruption ($\tau_w = 0.5\ s, T_e = 5\ eV, n_e = 10^{22}m^{-3}$): Left: Plasma and RE currents vs time (black lines); Right: Time evolution of the electric field (black line). The deconfinement takes place at $\xi_0 = 0.22$ and $\tau_d = 1\ ms$. The vertical line indicates the start of the scraping-off phase. The red lines show the results assuming no deconfinement ($\tau_d \to \infty$) (figs. taken from [6]).

The time evolution of the normalized vertical displacement, ξ, is plotted in left Fig.2. It should be noted the importance of the large enhancement of the electric field during scraping-off and deconfinement, resulting in a substantially larger energy deposition on the REs in comparison with the case with no deconfinement, as illustrated in Fig.2 (right), which compares the energy transferred to the REs in both cases ($\tau_d = 1\ ms$, and $\tau_d \to \infty$),

$$\Delta W_{run} \approx 2\pi R_0 \int_o^t I_r\left(E_{||} - E_R\right) dt' \ . \tag{5}$$

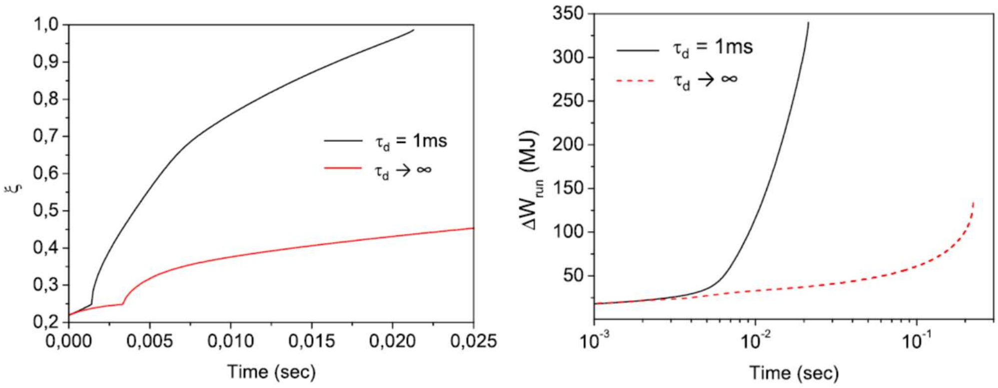

FIG.2 For the two examples discussed in Fig.1: Time evolution of the normalized vertical displacement, ξ, (left), and energy deposited on the REs, ΔW_{run}, (right) (black line: deconfinement at $\xi_0 = 0.22$, $\tau_d = 1\ ms$; red line: $\tau_d \rightarrow \infty$) (figs. taken from [6]).

The dependence of the conversion of magnetic into RE kinetic energy on the characteristic loss time, τ_d, and the resistive time of the residual ohmic plasma, τ_{res}, has been studied, as well as the effect of the initial RE current and the initial position of the RE beam. Hence, Fig.3 (left) shows ΔW_{run} as a function of τ_d for the same plasma conditions than Fig.1, initial position at deconfinement $\xi_0 = 0.22$ (before the beam hits the wall) and different values of the initial RE current (from 2 to 8 MA). The conversion of magnetic into RE kinetic energy is found to increase with τ_d, and the reduction of ΔW_{run} to sufficiently low values would require deconfinement times lower than 0.5 ms and, in such cases, no recovery of the RE current due to avalanche is found. Although ΔW_{run} increases with I_r^0, the dependence however is weaker. Also, larger resistive times (for example, due to larger T_e), τ_{res}, of the companion plasma during deconfinement, are efficient in reducing the amount of energy transferred to the REs. As a result, ΔW_{run} increases with τ_d/τ_{res} (see right Fig.3; the figure is obtained with $\tau_d = 0.1 - 2\ ms$, and $T_e = 5 - 10\ eV$).

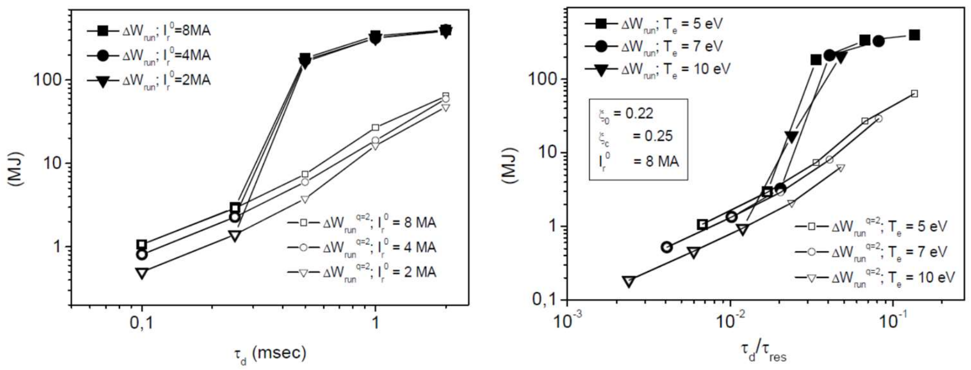

FIG.3 Left: Energy deposited on the RES, ΔW_{run}, versus characteristic RE loss time, τ_d, for three different values of the initial RE current (2, 4, and 8 MA); Right: ΔW_{run} versus τ_d/τ_{res} ($I_r^0 = 8\ MA$). The initial vertical position of the beam at deconfinement is $\xi_0 = 0.22$, and the plasma conditions are the same than in previous figures. The open symbols correspond to the energy deposited until q_a =2 is reached, $\Delta W_{run}^{q=2}$ (figs. taken from [6]).

The energy conversion has also been analyzed as a function of the initial vertical plasma position at deconfinement. Cases with the deconfinement starting before and after the plasma hits the wall have been considered (left Fig. 4; in these examples the contacts the wall at the normalized vertical displacement $\xi_c = 0.25$). Although ΔW_{run} is somewhat larger when the deconfinement starts during scraping-off, the difference is not strong. Only when the deconfinement starts well inside the scraping-off phase, the energy transferred to the REs might noticeably be larger for low enough values of τ_d.

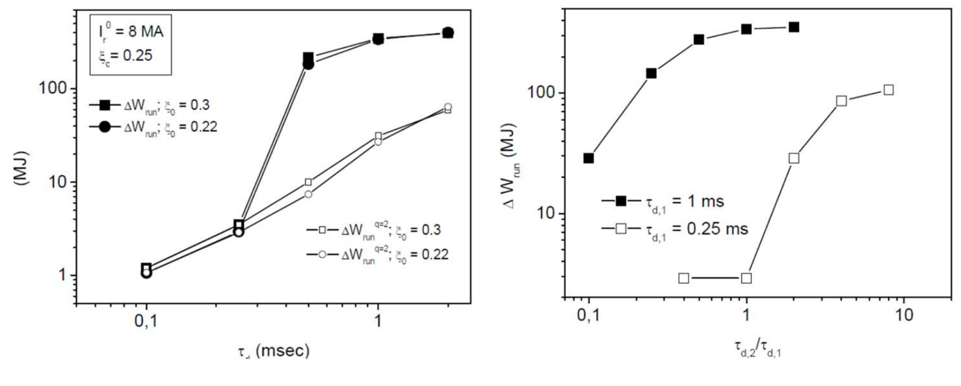

FIG.4 For the same plasma conditions than in previous figures and I_r^0 = 8 MA: Left: Comparison between the energy deposited on the RE beam for ξ_0 = 0.3 (deconfinement during scraping-off) and ξ_0 = 0.22 (deconfinement before the plasma hits the wall). $\Delta W_{run}^{q=2}$ (open symbols) is also indicated (ξ_c = 0.25 is the value of the normalized vertical displacement when the plasma touches the wall); Right: ΔW_{run} calculated assuming RE loss times τ_{d1} = 0.25 ms (open squares), τ_{d1} = 1 ms (black squares) before q_a = 2, as function of the ratio τ_{d2}/τ_{d1} (τ_{d2} is the RE deconfinement time after q_a = 2 is reached). The deconfinement starts at ξ_0 = 0.22.

The model does not take into account self-consistently the limitations on the safety factor, $q_a \equiv q(r=a)$, imposed by the MHD. For the cases here studied, the initial q_a of the plasma is larger than 2. Hence, as due to the decrease of the RE beam radius, the limit $q_a = 2$ is reached, it would not be correct to assume that the REs are lost with the same deconfinement time, τ_d, all the time, but the nature of deconfinement can change after $q_a = 2$ is crossed. Figs. 2 and left Fig.3 include (white symbols) the amount of energy deposited on the REs by the time $q_a = 2$ is reached ($\Delta W_{\rm run}^{q=2}$), which is substantially lower than the values obtained assuming the full scraping-off of the current with the same τ_d (black symbols), unless $\tau_d < 0{,}5$ ms, when the amount of energy deposited on the REs following $q_a = 2$ is negligible and so $\Delta W_{run} \sim \Delta W_{run}^{q=2}$.

Right Fig.3 illustrates, for the same plasma conditions than previous figures, $\xi_0 = 0.22$ and $I_r^0 = 8$ MA, the effect that a change of confinement after $q_a = 2$ might have. The calculated ΔW_{run} assuming RE loss times $\tau_{d1} = 0.25$ ms (open squares), $\tau_{d1} = 1$ ms (black squares) before $q_a = 2$ is plotted as function of the ratio τ_{d2}/τ_{d1} (τ_{d2} is the RE deconfinement time after $q_a = 2$ is reached). $\tau_{d2} > \tau_{d1}$ increases the conversion of magnetic into RE kinetic energy, whereas $\tau_{d2} < \tau_{d1}$ decreases ΔW_{run}, the amount of energy deposited on the REs increasing for larger τ_{d1}. Moreover, it is found that if the RE deconfinement time before the limit $q_a = 2$ is small enough ($\tau_{d1} < 0.1$ ms) , ΔW_{run} will be negligible for any value of τ_{d2}.

3. REs FOLLOWING MAGNETIC STOCHASTICITY AND HEALING

In this section, the three-loop model used in Sec.1 is going to be used to make a simple evaluation of the effect of a stochastization of the magnetic field for a finite time interval during the CQ of the disruption, followed by the reformation of the flux surfaces, on the RE current and the energy deposited on the REs in vertically unstable plasmas, including the effect of scraping-off when the beam contacts the wall. The RE losses are again described by a characteristic loss time, τ_d, and τ is the duration of the stochastic phase, after which the reformation of the magnetic flux surfaces occurs ($\tau_d \to \infty$).

Figure 5 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 $\tau_d = 2$ ms, starting at t = 0 s, extends during the CQ phase of the disruption for a period of $\tau = 5$ ms. The initial RE seed is $I_{seed} = 0.03$ MA. The time evolution of the plasma and RE currents are plotted in left Fig. 5 (black lines). The results assuming no RE 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.

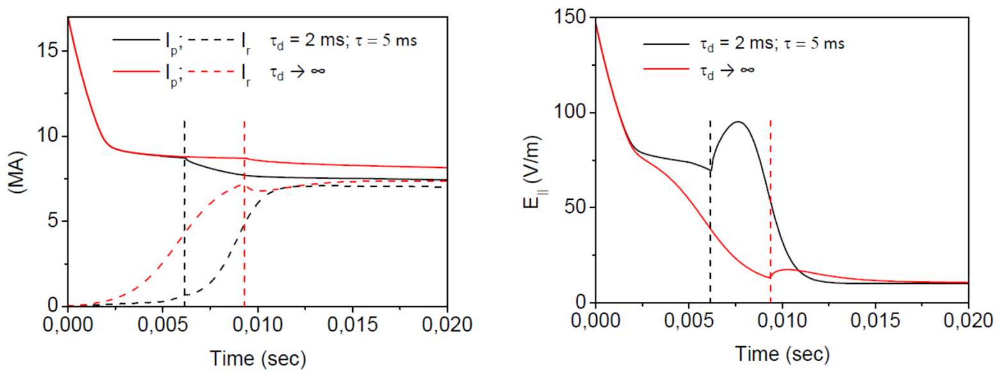

FIG.5 For a 15 MA ITER-like pre-disruption plasma current, assuming I_{seed} = 0.03 MA, T_e = 5 eV, n_e = 102^2 m^{-3}, and RE losses with characteristic deconfinement time τ_d = 2 ms for τ = 5 ms during the CQ (black lines): Time evolution of plasma and RE currents (left), and electric field (right). The red lines show the results assuming no RE losses ($\tau_d \to \infty$), and the vertical lines indicate the time the plasma hits the wall.

However, the reduction in the RE current leads to a larger plasma vertical velocity [2] and, therefore, to an increase of the electric field during scraping-off (right Fig. 5), resulting in a substantial amount of energy deposited on the REs, ΔW_{run} (left Fig. 6). Hence, when the surface $q_a = 2$ is reached, $\Delta W_{run}^{q=2}$~ 35 MJ, and the total amount of energy transferred during scraping-off is ΔW_{run} ~ 120 MJ ($\Delta W_{run}^{q=2}$~ 49 MJ and ΔW_{run} ~ 130 MJ for the case with no RE losses, $\tau_d \rightarrow \infty$). For illustration, right Fig. 6 presents the time evolution of the normalized vertical plasma displacement, ξ.

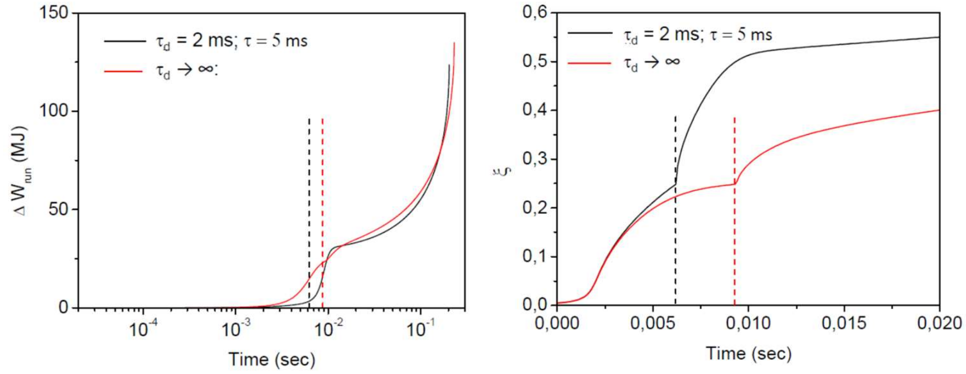

FIG.6 For the same disruption conditions and stochasticity parameters (τ_d and τ) than Fig. 5: Energy deposited on the REs (left), ΔW_{run}, and normalized vertical displacement (right),, ξ, as a function of time.

Thus, it is of interest to investigate, taking into account the effects associated with the scraping-off of the RE beam, the conditions under which the loss of REs during the CQ of the disruption might lead to a non harmful scenario from the point of view of the energy deposited on the REs.

Figure 7 shows, for the same disruption conditions than Figs. 5 and 6, the RE current when the plasma touches the wall, I_r^c, as a function of τ/τ_d for three different levels of stochasticity (τ_d = 0.5, 1, and 2 ms). It is found that I_r^c follows an approximate exponential behaviour with τ/τ_d, $I_r^c \sim \exp(-\tau/\tau_d)$ (Fig. 7). However, if the stochastic phase is sufficiently long and it finishes after the plasma contacts the wall ($\tau > t_c$, where t_c is the time to reach the wall), the RE current at contact saturates, $I_r^c = I_r(t = t_c)$, corresponding to the horizontal lines shown in the figure. In this case, it is found that the lower τ_d is, the larger the minimum value of τ/τ_d ($\equiv t_c/\tau_d$) required for saturation will be and, hence, I_r^c saturates at a smaller value, as illustrated in the figure where I_r^c is observed to saturate at ~ 0.4 MA for τ_d = 2 ms, ~ 20 kA for τ_d = 1 ms, or ~ 50 A for τ_d = 0.5 ms.

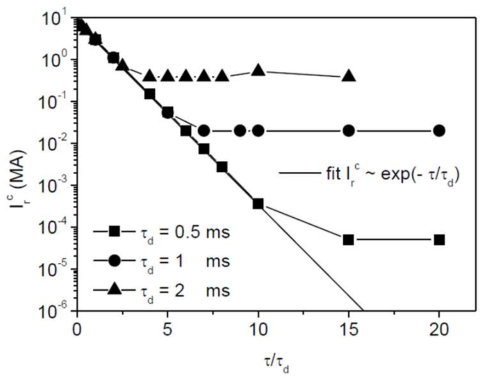

FIG.7 RE current at the time the plasma contacts the wall, I_r^c, as a function of τ/τ_d. The disruption conditions are the same than in Figs. 5 and 6 (squares: τ_d = 0:5 ms; circles: τ_d = 1 ms; triangles: τ_d = 2 ms).

The energy transferred to the REs during scraping-off as a function of τ/τ_d is plotted in left Fig. 8. When the stochasticity period extends to the scraping-off phase ($\tau > t_c$), ΔW_{run} increases, mainly because the lower RE current due to the losses leads to a faster vertical plasma motion and, so, to a larger electric field, increasing the RE avalanche unless the losses are sufficiently strong (as for the case τ_d = 0.5 ms). Nevertheless, as discussed in Sec. 2.2, it must be taken into account that the deposition of energy onto the RE electrons should not occur during the whole scraping-off phase, as the limit the limit $q_a = 2$ is reached, so that a deconfinement of the RE beam must take place following $q_a = 2$. Thus, right Fig. 8 presents the energy deposited on the REs by the time $q_a = 2$ is reached, $\Delta W_{run}^{q=2}$, noticeably smaller than the values calculated for the full scraping-off of the beam (left figure).

$\Delta W_{run}^{q=2}$ decreases when τ/τ_d increases unless the beam hits the wall during the stochastic phase, leading to the saturation of $\Delta W_{run}^{q=2}$ with τ/τ_d to a constant value which decreases for low τ_d (from ~ 15MJ for τ_d = 2 ms, to ~ 0.1 MJ for τ_d = 2 ms). If the deconfinement time following q_a = 2 is sufficiently small (< 0.1 ms), negligible additional conversion magnetic into RE kinetic energy would be expected after q_a = 2.

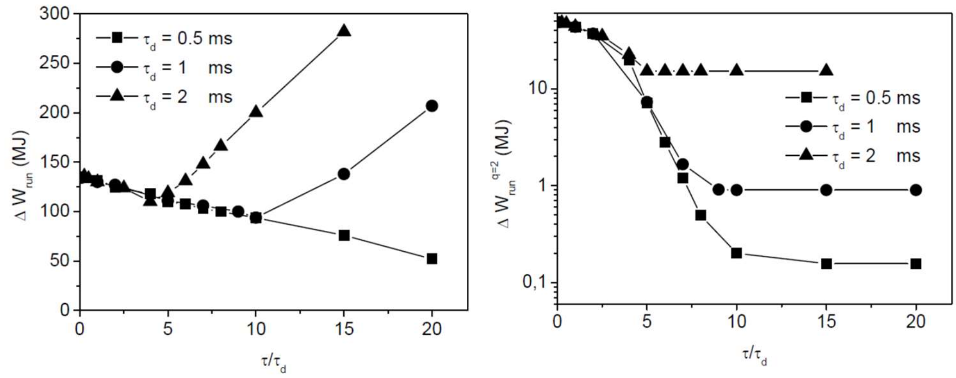

FIG.8 For the same disruption conditions than previous figures, energy transferred to the REs during scraping-off (left), and energy deposited on the REs when q_a = 2 is reached (right) vs τ/τ_d.

4. CONCLUSIONS

In the first part of this work, the effect of the motion and scraping-off of vertically unstable plasmas during fast deconfinement of disruption generated REs under ITER-like conditions has been investigated. A 0D three loop model for the plasma current and the currents in the wall has been used with that aim. The decay of the RE current during deconfinement leads to the acceleration of the plasma and a large increase of the electric field when it contacts with the wall during scraping-off, resulting in substantial RE avalanche which can yield the recovery of the RE current and a noticeable increase in the amount of energy transferred to the REs. The conversion of magnetic into RE kinetic energy, ΔW_{run}, increases with the characteristic RE deconfinement time, τ_d, and decreases when the resistive time, τ_{res}, of the companion plasma increases, due to the larger induced ohmic current and, overall, ΔW_{run} increases with τ_d / τ_{res}. The dependence of ΔW_{run} on τ_d and τ_d / τ_{res} is non-monotonic, reaching quasi-saturation for τ_d / τ_{res} larger than ~ 0.1. The conversion of magnetic energy into RE energy is larger when the deconfinement starts closer to the wall or during the scraping-off phase, but the effect is not strong unless it occurs place well inside the scraping-off phase (at large enough initial ξ values).

Secondly, the effect of the magnetic stochasticity during the CQ phase of vertically unstable disruption generated RE beams has been studied, focusing on the conditions required to avoid substantial energy deposition on the REs and damage on the PFCs during the scraping-off of the beam. Strong enough losses (low characteristic RE loss time, τ_d) for a sufficiently long stochastic phase (τ) are required to control the amount of energy transferred to the REs. Both, I_r^c and $\Delta W_{run}^{q=2}$ decrease when τ/τ_d increases (approximately exponentially in the case of I_r^c, $\sim\exp(-\tau/\tau_d)$), unless the beam contacts the wall during the stochastic phase, leading to saturation for $\tau > t_c$, I_r^c and $\Delta W_{run}^{q=2}$ at saturation decreasing for small τ_d. Hence, for example, for low temperatures of the residual ohmic plasma during the disruption in ITER ($\sim$ eVs), to reduce ΔW_{run} to a few MJs or below, it is found that deconfinement times τ_d < 1 ms and τ/τ_d > 5 would be required. Moreover, independently of the model used for the magnetic stochasticity and the RE losses, it is found that the relevant parameter determining the energy deposited on the REs during scraping-off is the RE current at the time the plasma hits the wall, I_r^c, and this study suggests that I_r^c should be kept quite low, in a range ~few kAs to tens of kAs. Nevertheless, it should be taken into account that the model does not consider halo currents, which could help to stabilize the RE beam, and increase the resistive decay time of the thermal plasma, which effect should be analyzed in a future work

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