Profile Effects on the Dissipation of Runaway Beams by Impurity Injection in Tokamak Disruptions

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1. Introduction Two layers of defense have been proposed for runaway electron (RE) mitigation during disruptions: (1) RE avoidance, i.e., preventing the generation of MA RE currents; (2) mitigating the wall impact of the RE beam by Shattered Pellet Injection (SPI) in case that its formation cannot be avoided. In the past, the mitigation of MA RE currents by injection of high-Z species was investigated by means of 0-D modeling [1]. In this work, a 1D model is used to address the dissipation of RE beams by impurity injection. It is found that initially peaked RE current density profiles result in a slower current dissipation, the effect increasing with the peaking of the current profile. Effects associated with a localised deposition of the impurities are also discussed.

2. Model equations A one-dimensional (1-D) model, including the evolution of the plasma and RE current density profiles during the dissipation of the RE beam, has been used [2]. It considers a straight, circular cylinder ($r < a$; a is the plasma minor radius) surrounded by a thin conducting wall with a finite resistivity. The evolution of the plasma current density profile ($j_p(t,r)$) is calculated solving the current diffusion equation:

$$\mu_0 \frac{\partial j_p}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial E_{||}}{\partial r}\right] = \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial \eta (j_p - j_r)}{\partial r}\right], \tag{1}$$

with $E_{||} = \eta\,(j_p - j_r)$ ($j_{p,r}$ are the plasma and RE current densities, respectively).

When the impurities are injected, the electric field drops below the critical electric field for RE generation and the dissipation of the RE current occurs. Following [1], assuming for simplicity collisional losses only and an initial avalanche-like exponential runaway energy distribution function, the RE current density decay can be written [1]

$$\frac{\partial j_r}{\partial t} \approx \frac{ec\left(E_{||} - E_R\right)}{T_r}\, j_r, \tag{2}$$

where T_r is the characteristic exponential energy decay of the initial runaway distribution, and E_R is the critical electric field for RE generation given, including the effect of the collisions with the free and bound electrons of the impurities, by $E_R \approx e^3\,\alpha_e/(4\pi\,\varepsilon_0^2\,m_e c^2)$, with $\alpha_e \equiv n_{ef}\ln\Lambda_{ef} + n_{eb}\ln\Lambda_{eb}$ (n_{ef}, n_{eb} are the free and bound electron densities, respectively, and $\ln\Lambda_{ef}$, $\ln\Lambda_{eb}$ the Coulomb logarithms for the collisions of the REs with the free and bound electrons) [2]. Effects associated with the induced currents in the vessel and the penetration of external magnetic energy are not considered.

The RE kinetic energy dissipated per unit volume after time t is estimated

$$\Delta w_{run} = \int dt'\, j_r \left(E_{||} - E_R\right) = \frac{T_r}{ec}\left(j_r - j_r^0\right) \tag{3}$$

(j_r^0 is the initial runaway current density) where Eq. (2) has been used, and the total dissipated energy is given by (I_r^0 is the initial runaway current):

$$\Delta W_{run} = \int dv\, \Delta w_{run} = \frac{2\pi R_0 T_r}{ec}\left(I_r - I_r^0\right). \tag{4}$$

3. Current profile shape effects It is expected that the RE current generated during the disruption will be more peaked in the central plasma region than the pre-disruption plasma current density profile. This peaking can have important consequences for the dissipation of the runaway beam. This is illustrated in Fig. 1 and 2, corresponding to the mitigation of a 10 MA plateau runaway current in ITER by $2\,\mathrm{kPa}\cdot\mathrm{m}^3$ Ne injection[1], and radially uniform impurity deposition. The plateau RE current is peaked in the center, with $l_{int}^0 = 1$ (l_{int}^0: internal inductance of the RE current). The hydrogen density is $n_H = 10^{20}\,\mathrm{m}^{-3}$, and $T_e \sim 3\,\mathrm{eV}$. Fig. 1 shows the radial profiles of the current density (left) and electric field (right) at different times during current mitigation. When the impurities are injected, the critical field (E_R) increases and the current decays: due to the peaking of the plateau current, the RE current density is larger in the plasma center and the induced electric field during current decay increases close to the critical field (marginal stability scenario [1]), while in the outer region, with a lower j_r, the induced electric field is smaller, and is far from the marginal stability. Thus, the drop of the RE current is slowed down in the center of the plasma and accelerated in the outer region (left Fig. 1). The resulting energy dissipation also mostly occurs in the outer plasma region (left Fig. 2). The larger the central peaking of the current is, the larger the current density in the plasma center and so the induced electric field during current decay, so that the dissipation efficiency decreases when the plateau current peaking increases, This is illustrated in right Fig. 2 which compares, for two values of l_{int}^0 (1 and 2) of an initial

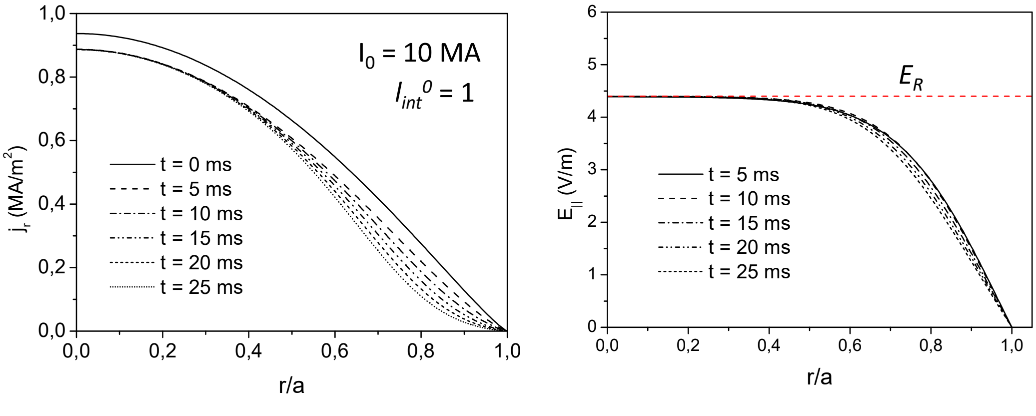

Figure 1: For the mitigation of an ITER-like 10 MA RE current plateau by $\sim 2\,\mathrm{kPa}\cdot\mathrm{m}^3$ Ne injection: RE current density (left) and $E_{||}$ (right) vs. r/a at different times during current decay (the horizontal red line indicates E_R after Ne injection). The internal inductance of the initial plateau RE current is $l_{int}^0 = 1$, $n_H = 10^{20}\,\mathrm{m}^{-3}$, and $T_e \sim 3\,\mathrm{eV}$.

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[1] In ITER, $1\,\mathrm{kPa}\cdot\mathrm{m}^3 \sim 2.5\times10^{23}$ atoms.

ITER-like 10 MA RE current, the predicted RE current during dissipation at a typical time in ITER for the vertical instability growth ($\sim 100\,\mathrm{ms}$) as a function of the amount of assimilated Ne.

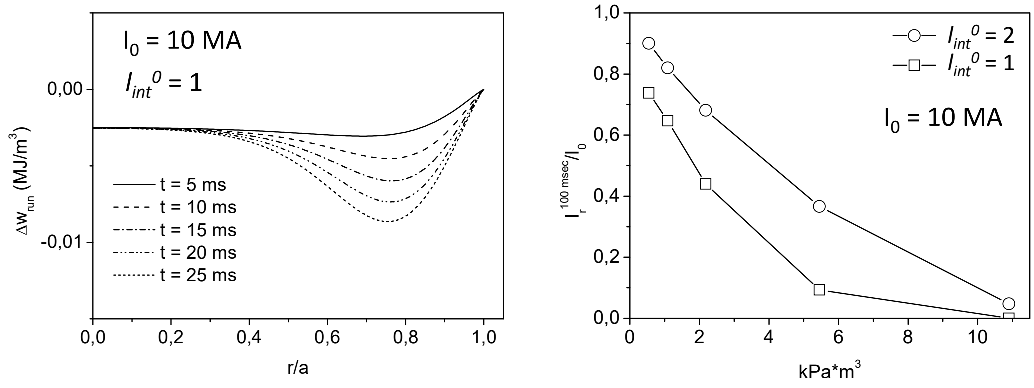

Figure 2: For the same conditions than Fig. 1: Left: Dissipated RE kinetic energy per unit volume, Δw_{run}, vs. r/a at different times during current mitigation ($l_{int}^0 = 1$); Right: Predicted RE current at 100 ms, normalized to the plateau current, vs. the amount of Ne injected for two different values of the peaking of the plateau current ($l_{int}^0 = 1$ and 2).

3. Non-uniform impurity deposition The previous analysis has assumed a radially uniform impurity deposition. However, radially localized deposition profiles are expected. Fig. 3 presents the results for the dissipation of a 10 MA RE current ($l_{int}^0 = 1$) by $2\,\mathrm{kPa}\cdot\mathrm{m}^3$ Ne injection and the initial deposition profile of Fig. 3 (a), under the same plasma conditions than Fig. 1. As shown in Fig. 3 (b), a strong drop of j_r occurs in the main deposition region, where $E_{||} < E_R$, while the RE current density increases in the inner region as a result of the inward diffusion of the electric field where $E_{||} > E_R$. Also, whereas a strong energy dissipation occurs in the main deposition region, energy is transferred to the REs in the center of the plasma (Fig. 3 (c)), which overall reduces the dissipation efficiency.

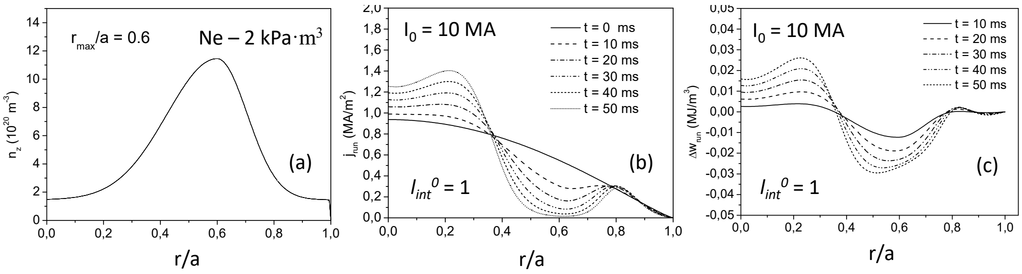

Figure 3: For the mitigation of an ITER-like 10 MA RE current under the same plasma conditions than Fig. 3, by $\sim 2\,\mathrm{kPa}\cdot\mathrm{m}^3$ Ne injection and impurity deposition profile of Fig. (a): j_r (b) and Δw_{run} (c) vs. r/a at different times during the current decay.

The dependence of the dissipation efficiency on the impurity penetration has been explored. This is illustrated in Fig. 4 which shows the RE current and the dissipated RE kinetic energy at 100 ms during the current decay as a function of the amount of Ne (in $\mathrm{kPa}\cdot\mathrm{m}^3$) for different locations for the maximum deposition (r_{max}/a) but the same deposition profile shape. The case of a radially uniform impurity deposition is also presented, showing the largest dissipation efficiency. In contrast, the lowest dissipations are found for the innermost and outermost impurity depositions, unless MHD effects that promote mixing or impurity radial transport can play a role.

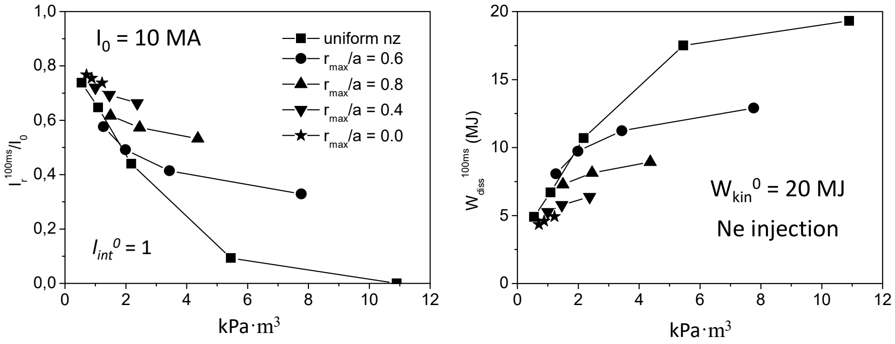

Figure 4: For the same initial conditions ($I_r^0 = 10\,\mathrm{MA}$, $W_{kin}^0 = 20\,\mathrm{MJ}$) and impurity deposition profile shape than Fig. 3: RE current (left) and dissipated RE kinetic energy (right) at 100 ms vs. injected Ne (in $\mathrm{kPa} \cdot \mathrm{m}^3$) for different values of r_{max}/a. The case of a radially uniform impurity deposition is also shown.

4. Conclusions Profile effects on the mitigation of a disruption plateau RE current by injection of high-Z impurities have been investigated. First, effects associated with the shape of the plateau RE current density profile have been considered. It has been found that initially peaked current density profiles, as those expected during the current quench phase of a disruption, result in a slower current dissipation, the effect increasing with the peaking of the current profile. Second, effects associated with the radial shape of the impurity deposition profile have been considered. For radially localized impurity deposition, RE energy and current are dissipated in the main deposition region but, due to the radial inward diffusion of the electric field, the RE current is increased and energy deposited on the REs in the plasma center. Hence, the most efficient dissipation is found for radially uniform impurity deposition. Furthermore, the dissipation efficiency is found to decrease for too inner or outer impurity deposition, making the control of the impurity penetration depth critical for RE dissipation.

Acknowledgements The authors wish to thank prof. A. de Castro for invaluable support, and Dr M. Lehnen for his wise advice on the RE topic along these years. This work was done under financial support from Ministerio de Ciencia, Innovación y Universidades (Spain), Project No.PID2022-137869OB-I00, and carried out under the coordinated research programme of the Disruption and Runaway Theory and Simulation group of the ITER Scientist Fellow Network. ITER is the Nuclear Facility INB no. 174. This paper explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results of this paper. The views and opinions expressed herein do not necessarily reflect those of ITER.

References

[**1**] J.R. Martín-Solís et al., in Fusion Energy 2018 (Proc. 27th Int. Conf., Ahmedabad, 2018) (Vienna: IAEA) CD-ROM file TH/4-1.

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