Linear ideal and resistive MHD stability analysis of post-disruption plasmas with runaway electrons in ITER

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Most of the plasma current can be replaced by a runaway electron (RE) current during plasma disruptions in ITER [1]. In this case, the post-disruption plasma current profile is likely to be more peaked than the pre-disruption profile [2]. Such plasmas may become MHD unstable. This would affect the runaway electron generation and confinement and the dynamics of the plasma position evolution (Vertical Displacement Event (VDE)), possibly limiting the time frame for RE and disruption mitigation.

For the evaluation of possible MHD instabilities in post-disruption plasmas in ITER, we calculate the self-consistent evolution of the plasma equilibrium during a VDE event with the free boundary equilibrium code DINA [4], starting with a prescribed seed RE current profile and a prescribed impurity profile. The linear ideal and resistive MHD stability of the resulting sequence of equilibria is then analyzed with the codes MISHKA [5] and CASTOR [6].

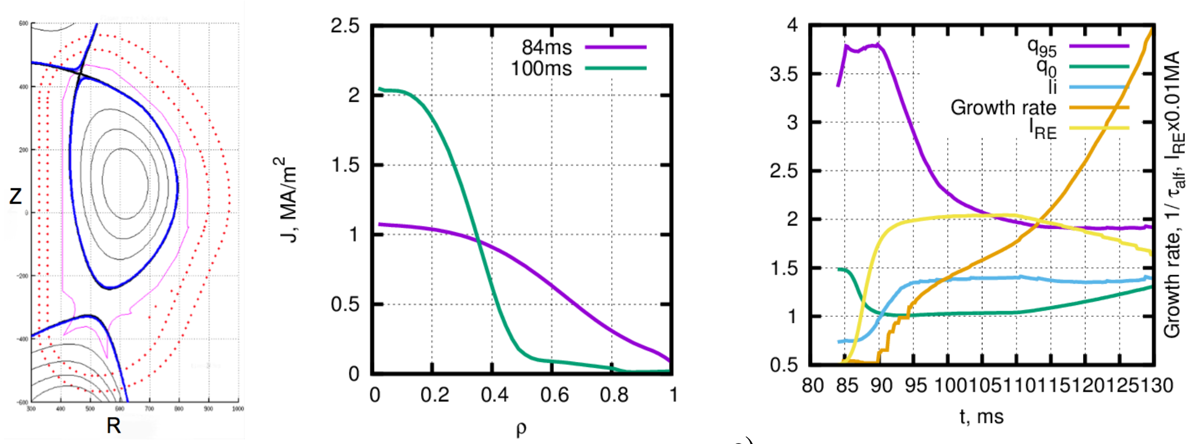
We start the DINA VDE calculations from an equilibrium of the 15MA Q=10 ITER scenario. We prescribe the Thermal Quench (TQ) event to happen, leading to a plasma temperature drop and a flattening of the q-profile inside q=2 flux surface. We also assume that a constant and flat Ar impurity density of $0.25 \cdot 10^{20} m^{-3}$ was introduced in the pre-TQ phase to mitigate thermal loads. This amount of Ar is enough to keep the post-disruption temperature low and provide a high inductive electric field to initiate a RE avalanche. In the present study, we side-step the questions of primary RE generation and prescribe the seed RE current profile. We use a Gaussian profile for the RE seed current, and our parametric scan involve a variation of the Gaussian profile width (w) and amplitude:

$$j_{seed} = j_0 e^{-\frac{\rho^2}{w^2}},$$

where ρ is a minor radius.

The subsequent evolution of the plasma equilibrium is calculated self-consistently with the RE generation (via avalanche mechanism [1]), resulting in the evolution of the total plasma current profile as well as the whole equilibrium.

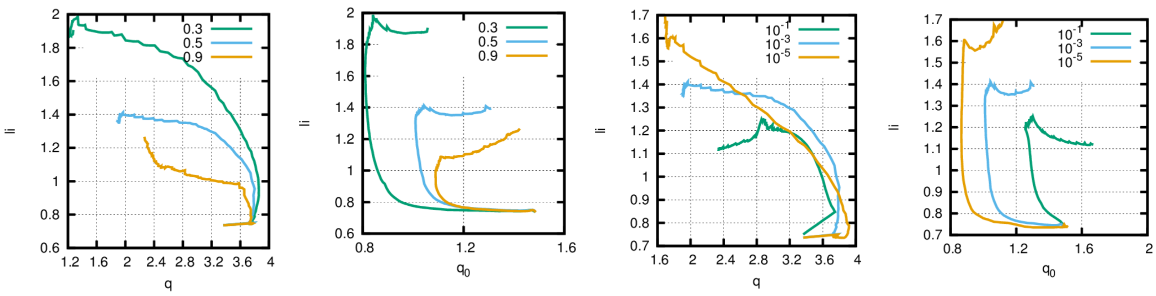
An example of such evolution (for the RE seed current of 22kA) is plotted in Figure 1. In this case the TQ occurs at 84ms, and then the avalanche quickly multiplies the RE current profile resulting in a total RE current of 8MA by 95ms. During this evolution, due to the contraction of the total current profile (Fig. 1-2)) the internal inductance l_i grows from the initial value of 0.6 to 1.4, while the value of q at the magnetic axis and at the boundary drops significantly.



a) b) c)

Fig. 1. The evolution of the plasma equilibrium for the RE seed current of 22kA: a) plasma shape b) "shrinking" of the total current profile c) time evolution of the the internal kink growth rate, q, q_o , l_i and I_{RE}

It is reasonable to expect that $q \leq 1$ at the axis will give a rise to a sawtooth-like mode and integer q at the boundary will result in an external kink instability. For brevity, we will provide only $q - l_i$ plots of other studied cases (see figure 2). In most of these cases q_a approaches 1.



a) b) c) d)

Fig. 2. a) q_{95}-li and b) q_0-li plots for different RE current profile width (w is indicated in the legends) and I_0 =22kA c) q_{95}-li and d) q_0-li plots for different on RE seed amount (j_0 is indicated in the legends) and w=0.5.

Whilst ideal MHD modes are insensitive to the nature of plasma current, the resistive MHD instability in the runaway plasmas was investigated in [3]. It was shown that linear growth rate of resistive modes in a runaway-dominated plasma is approximately the same as in the plasma without runaways. We thus rely on these findings and proceed to a linear ideal and resistive MHD stability analysis of the resulting sequence of equilibria with MISHKA [5] and CASTOR [6] codes. MISHKA is an ideal, incompressible MHD code. In CASTOR, the linearized resistive MHD equations are solved in a general toroidal geometry, where the equilibria are assumed to be axisymmetric and static. We calculate the linear growth-rates of ideal MDH modes with both codes for crosscheck.

Figure 3a shows the evolution of the linear growth rate for the cases shown previously in Figs. 1 and Fig. 2. In all these cases, the dominant mode is an internal resistive kink mode with n=m=1. An example of the evolution of the structure of this mode is shown in Fig.3b.

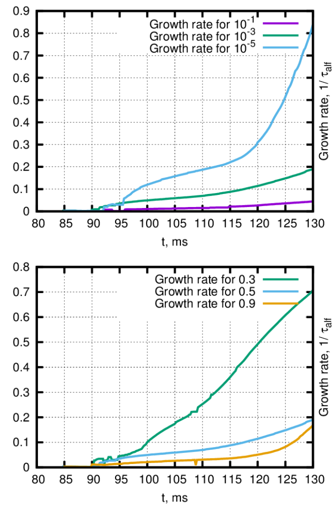


Fig.3a Time evolution of the internal kink growth rate dependence on the RE seed amplitude, w=0.5 (up) and RE current profile width, I_0=22kA (down).

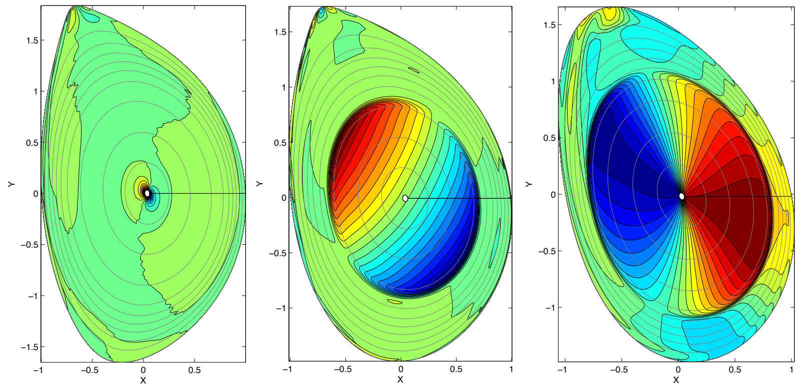


Fig.3b The evolution of the internal kink mode during a VDE I_0=22kA, w=0.5. (shown is structure of the displacement of the perturbation in the poloidal plane.)

This mode is present (and dominant) in most of the analyzed cases, and although it has relatively high growth rate it is not expected to significantly affect the course of VDE [7]. This mode will most likely result in a flattening of the current profile (this effect is not taken into account self-consistently in the current study). Omitting this mode from the consideration, we find that a variety of other modes develop in during the profile evolution. The growth rate and a selection of mode structures are shown in Fig.4a. Two extreme cases (narrow profile *w*=0.3 case and low seed current I_0=0.2kA case) result in a very peaked current profile (with no current on the periphery) giving rise to internal modes (Fig.4b -3,6). On the other hand, a smooth and high-seed RE profile (*w*=0.9 and I_0=2.2MA cases) provides more current at the boundary accompanied by external kink and q=2 tearing modes (Fig.4b -1,4) which may result in fast bursts and RE losses [8]. The intermediate case (I_0=22kA, *w*=0.5) shows moderate external kink instability when q_{95} approaches integers (Fig.4b -2,5).

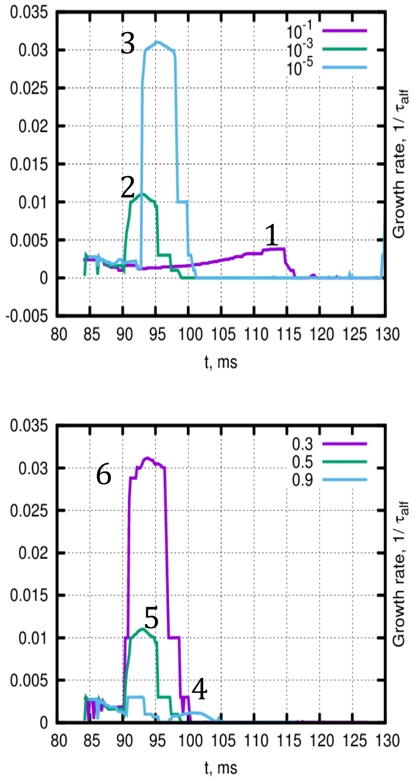


Fig.4a Time evolution of growth rate dependence on the RE seed amplitude, w=0.5 (up) and RE current profile width, j_0=22kA (down) excluding m=n=1 mode.

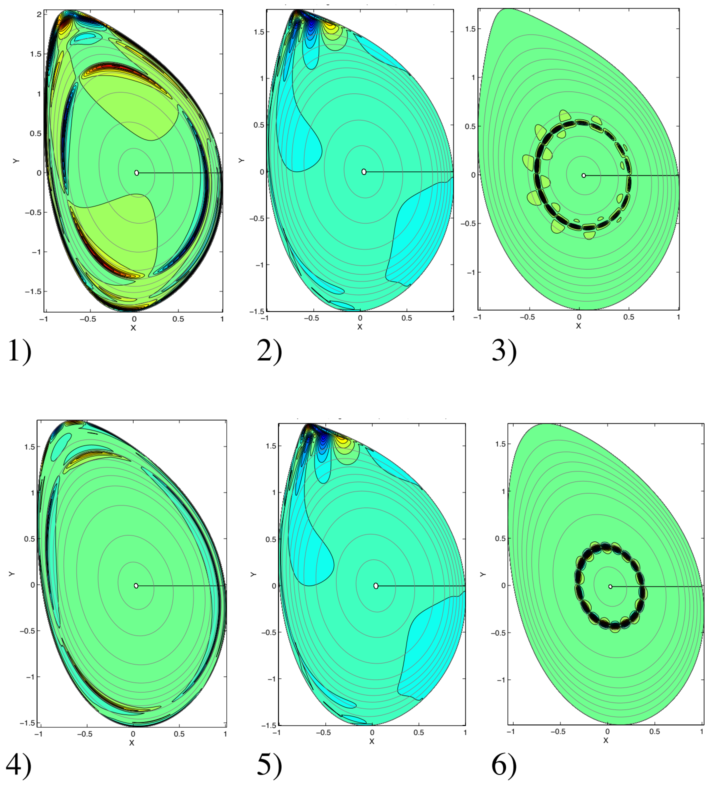


Fig.4b Structure of the modes (excluding m=n=1 mode) which can develop during the evolution of the RE current profile in ITER disruptions. Dependence on RE seed amplitude, w=0.5 (up, 1-3) and RE current profile width j_0=22kA (down, 4-6)

In summary, we conclude that both ideal and resistive modes (internal kink modes, tearing modes and external kink modes) can develop during the evolution of the RE current profile in ITER disruptions. These modes can significantly affect the RE confinement and a course of the VDE. External modes are more pronounced for higher and broader initial RE seeds, tearing modes are present in both extreme cases (while absent in the intermediate case), and almost any initially peaked RE seed profile causes an internal m=n=1 mode. Further investigations are required to derive a desirable disruption scenario for ITER, and non-linear MHD dynamics needs to be taken into account for the VDE evolution.

References

[1] M. N. Rosenbluth, S. V. Putvinski, Nucl. Fusion 37, 1355, (1997)

[2] L.G. Eriksson, P. Helander, F. Andersson, D. Andersson and M. Lisak,Phys. Rev. Lett. 92, 205004 (2004).

[3] Helander P., Grasso D., Hastie R.J. and Perona A. 2007 Phys. Plasmas 14 122102

[4] R. Khayrutdinov and V. Lukash, J. Comput. Physics 109 (1993) 193-201

[5] A. Mikhailovskii, G. T. A. Huysmans, W. O. K. Kerner, and S. Sharapov, Plasma Phys. Rep. 23, 844 1997

[6] W Kerner, JP Goedbloed, GTA Huysmans, S Poedts, E Schwarz. J. of comput. Phys. 142(2),271-303, (1998)

[7] Huishan Cai and Guoyong Fu, Nucl. Fusion 55, 022001, 2015

[8] Smith H.M., Feher T., Fülöp T., Gal K. and Verwichte E. 2009 Plasma Phys. Control. Fusion 51 124008